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A TRIAL TO INVESTIGATE AIR-TO-AIR U.H.F. AND MICROWAVE PROPAGATION AT LOW ALTITUDE [S]

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SUMMARY

Flight trials in support of a Weapons Department research programme were conducted over varying types of terrain and varying sea states, to determine the suitability of U.H.F. or X-band in an air-to-air radio link capable of carrying television and command data.

The results of the over sea trials accorded well with theory except that fading nulls at U.H.F. could be greater than the theoretical value.

Analysis of results of over land flights indicated that at X-band most fades, and at U.H.F. many fades, could be attributed to signal reflection from metallic objects.

Differences in the fading characteristics observed on various headings were attributed to the disposition of reflecting objects and to terrain screening.

The results indicate that X-band offers the better performance by virtue of lower fade depths and briefer outages. ~~Factors such as~~ countermeasure susceptibility, aerial installation problems and costs are not considered.

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1 INTRODUCTION

The propagation flight trials described in this Report were undertaken by Radio Department in support of a Weapons Department research programme on tactical air-to-surface television-guided missiles. The object of the trials was to provide data on the propagation effects likely to be encountered at U.H.F. and X-band frequencies on air-to-air links operating over sea and over various types of terrain. The eventual choice of frequency for any particular missile to aircraft link involves factors such as countermeasure susceptibility, aerial installation problems, equipment complexity and relative costs, which are not dealt with in this paper. The over sea trials were carried out at Aberporth. Two of the over land paths were in the vicinity of Farnborough and a third in Cardiganshire near Aberporth.

With the exception of one series of tests flown to a range of 40 nm and a height of 20000 ft, the trials were flown to a basic flight pattern reasonably representative of the relative motions of aircraft and missile during a low-level air-to-surface attack in which the missile is assumed to be air-launched at a height of between 50 and 200 ft, climbs rapidly to 2000 ft, and flies at this height until directed into a dive on to the target.

To simplify the procedure and maintain a tight control over the path parameters, only one Canberra aircraft was used, representing the missile, which carried the U.H.F. and X-band transmitters. The ground receiving aerials were elevated to a height appropriate to the parent aircraft either by the use of a tower or by siting them on steeply sloping high ground.

2 AIRBORNE EQUIPMENT

The experimental X-band transmitter, designed around a 10 watt tunable C.W. magnetron (Mullard Type JPT 9/01) was mounted in the tail cone of the Canberra, and the aerial projected through the apex of the tail-cone. Views of the X-band transmitter and tapered waveguide aerial are shown in Figs.1 and 2 A stabilised power supply for the transmitter was installed in the after camera-hatch. The control unit comprising magnetron current control and indicating meter was mounted in the pressurised cabin, adjacent to the Navigator's seat.

The experimental X-band aerial was designed to meet the estimated requirements of a missile having a wide freedom in angle of attack in relation to the position of the launching aircraft. It was further considered that at X-band a front-to-back ratio of at least 20 dB could be achieved, which would afford useful protection against E.C.M. To meet the requirements of a rolling missile, a circularly polarised dielectric aerial with a roughly hemi-isotropic polar

diagram was developed based on a design of E.G.A. Goodall[1] and was flown successfully on some of the early trials. A vertically polarised post-loaded waveguide aerial was subsequently developed having beamwidths of about 110° in the horizontal plane and 90° in the vertical plane. This latter aerial was used for all the trials described in this Report.

An ARC.52 transmitter provided 20 watts of carrier power for the U.H.F. tests. The U.H.F. transmissions were radiated from an omni-directional vertically polarised blade aerial located beneath the fuselage, (Fig.3).

3 GROUND EQUIPMENT

3.1 Aerials

The design of the X-band receiving aerial was influenced mainly by consideration of the upper limit of aperture likely to be permissible on the parent aircraft. Initially, this limitation had not been precisely defined and it was decided therefore to design the aerial mounting arrangements to accommodate either 9 inch or 18 inch dishes, of which at least the former was thought to be well within acceptable limits. With dishes of these diameters, aerial beamwidths at X-band are about 10° and 5° respectively and it is clear that a lock-follow aerial system would be necessary to track a missile. However, for the purpose of the trials, a manually steerable aerial incorporating a telescopic sight was used.

The X-band aerial assembly (Fig.4) consisted of a tripod surmounted by a turn-table which supported the telescopic-sight, aerial, balanced crystal mixer, I.F. pre-amplifier and a signal strength indicator, which was used mainly for aligning the aerial and optical axes. The aerial was steerable in both horizontal and vertical planes.

An omni-directional wideband discone aerial was used for reception of the U.H.F. signals.

During the trials in the Farnborough area, the aerials were sited on the top of a 70 ft wooden tower at the Ewshot Receiving Station. For the over sea trials the aerials and the vehicle containing the receiving and recording gear were stationed at the Balloon Base, R.A.E. Aberporth, a concrete apron surmounting a 220 ft cliff. During the series of over land trials carried out in the Aberporth area, the receiving equipment was sited at OP21, an observation post belonging to R.A.E. Aberporth, which is situated on high ground sloping fairly steeply downwards in the vicinity of the station in the seaward direction.

The X-band aerial was mounted on the roof of the station building and the U.H.F. aerial on the top of a 30 ft mast.

3.2 Receiving and recording equipment

Fig.5 shows the overall experimental ground station installation in block schematic form. The main units of the equipment were installed in a 3 ton vehicle.

Dealing first with the X-band equipment, it will be seen in Fig.5 that the klystron oscillator was located within the vehicle and remote from the mixer. This necessitated a waveguide run between the vehicle and the aerial assembly but gave the advantage of bringing the receiver tuning under the control of the operators in the vehicle. From the I.F. pre-amplifier on the aerial assembly, the signal was fed into the main I.F. amplifier via a switched variable attenuator, which was adjusted as necessary during a run to maintain the signal at a suitable level for recording. The greater part of the trials were conducted with I.F. amplifiers of 5 Mc/s bandwidth centred on 38 Mc/s. However, for the 40 nm range tests and the second Aberporth series some wider bandwidth amplifiers had become available and were fitted, mainly to obviate the need to make frequency adjustments during runs. The centre frequency of these amplifiers was 60 Mc/s and the bandwidth 28 Mc/s. From the detector stage, the signal was taken via the metering and amplifying unit (essentially a d.c. amplifier) to the recorder and also to the local and remote indicators.

For the U.H.F. signals, a proprietary ground receiver (Collins Type R-278B/GR) was used. The signal was taken directly off the second detector and adjusted to the required recording level by means of a 4-position sensitivity control incorporated in a second d.c. amplifier.

Simultaneous recordings of the U.H.F. and X-band signals, together with time and event marks, were made on a multi-track photographic paper recorder (Type IT.3-12) running at 1 in/sec., and occasionally, in parallel on a high speed film recorder. Timing marks were derived from the 50 c/s mains frequency. A simple event marker system was provided whereby d.c. impulses were generated by a manually operated push-button. At the conclusion of each sortie calibration records were made using signals of pre-determined levels derived from signal generators.

4 FLIGHT PATTERNS

With the exception of some 40 mile range tests which are discussed below, the propagation trials described in this Report were limited to an investigation

of the path parameters typifying a low-level attack in which the missile is launched from the aircraft at a height of between 50 and 200 ft. It then climbs rapidly to 2000 ft and proceeds under radio guidance towards the target while the aircraft remains at low altitude. Finally, the missile is directed into a dive onto the target. It is required that the television and command links shall operate satisfactorily throughout the attack with aircraft to missile separation ranges of up to 20 nm.

While, it would be desirable to mount the trials with two aircraft in order to make the closest approach to the specified aircraft to missile trajectories, there are, in practice, serious objections to this approach. In the first place, the problems of aircraft availability would be aggravated. Secondly, the installation in an aircraft of the receiving and recording gear, and in particular, the steerable X-band aerial, would present further difficulties. Finally, with both ends of the link in motion, a sufficiently accurate determination of air-to-air distances would not be easy to achieve. It was considered therefore that reasonably representative results could be obtained more quickly and simply by adopting a basic flight pattern needing only one aircraft to represent the missile. This pattern, shown in profile in Fig.6, required the aircraft to overfly the receiving aerials at a height of 2000 ft and then proceed at this height along a pre-determined heading for a distance of 17 nm, finally descending at about 6° to a height of 250 ft when at 20 nm range. Some variants of this pattern were flown during the over land trials in the Farnborough area, mainly with the object of investigating the effects on the fading patterns of changes of aircraft altitude. These runs were carried out at heights varying between 1000 and 2500 ft. In some instances the final descent was omitted.

In an effort to obtain data relating to a possible high-level attack mode, a series of runs were flown on a totally different pattern. For these tests, the aircraft climbed at a uniform rate from 500 ft above the receiving aerials to 20000 ft when at a range of 40 nm.

5 TRIALS PROCEDURE

Trials runs, usually in groups of five or six, were flown in conditions of good visibility to the required height; this was a necessity for the X-band aerial operator and also for the air-crew.

At Farnborough, the recorded range information was derived from visual observations of pre-arranged land marks by the Air Navigator and passed over the

U.H.F. link to the ground station. Lock-follow radar was used to achieve the required navigational accuracy during over sea trials, which were flown over Cardigan Bay in the vicinity of R.A.E. Aberporth. The Aberporth lock-follow radar was used also for the trials based on OP21. Radar information, commencing at -5 nm, was given at every mile point to +21 nm over the Aberporth intercommunication system.

The recorder and the timing unit were switched on at -1 nm. The X-band aerial was trained on to the aircraft as soon as possible after the overhead position had been passed and thereafter the aerial operator followed the aircraft optically to the end of the run if visibility permitted. Otherwise, the aerial was locked at the position where visibility was lost. The ground operators adjusted the levels of the two signals at the recorder heads and made occasional checks for frequency drift.

6 PROPAGATIONAL ASPECTS

6.1 Range and S/N ratio at X-band

Before designing the X-band transmitter, an estimate was made of the transmitted power needed to ensure an output S/N ratio at the receiver of 6 dB during the worst expected fading nulls. In section 6.3.1 it is concluded that an output S/N ratio of at least 20 dB is required at or near maximum range under "free-space" conditions to provide the necessary margin for fading. This figure of 20 dB is used in the following calculation.

Thermal noise $N = KTB$, where K = Boltzmann's constant
T = Absolute temperature ($^{\circ}K$)
B = Bandwidth

For a bandwidth of 5 Mc/s and assuming $T = 293^{\circ}K$

$$\underline{KTB = -137 \text{ dBW}}$$

The input power (P_R) required to provide an output S/N ratio of 20 dB, assuming a receiver noise factor of 10 dB is then:-

$$P_R = -137 + 20 + 10$$
$$= -107 \text{ dBW}$$

The transmitted power (P_T) required to provide this value of P_R is:

$$P_T = P_R - G_T - G_R + L$$

where G_T and G_R are the gains of the transmitting and receiving aerials respectively, and L is the "free-space" attenuation at the range R

$$L = 20 \log \frac{4\pi R}{\lambda} \text{ dB} .$$

At the maximum range of 20 nm (36 km)

$$L = 144 \text{ dB}$$

G_T = 6 dB and G_R (for the 9 inch dish) $\simeq$ 23 dB

$$P_T = -107 - 6 - 23 + 144$$
$$= +8 \text{ dBW (or 6.3 watts)}$$

No losses have been assumed at either end and hence a power of 10 watts was considered insufficient for the 9 inch dish but adequate for the 18 inch dish, which has an additional gain of approximately 6 dB over the 9 inch dish.

6.2 U.H.F. propagation

In calculating the received power at maximum range under "free-space" conditions, it is assumed that the transmitter is rated at 20 watts, the total aerial gain is 4 dB and the system loss is 5 dB. For convenience, the frequency is here assumed to be 400 Mc/s (λ = 75 cm).

$$\text{Space attenuation} = 20 \log \frac{4\pi R}{\lambda}$$
$$= 116 \text{ dB}$$

Total losses are (116 + 5) dB = 121 dB
Transmitted power = 20 watts = 13 dBW .

Then

$$P_R = P_T + G_T + G_R - L$$
$$P_R = 13 + 4 - 121$$
$$= -104 \text{ dBW or } -74 \text{ dBm}$$

6.3 Fading

Radio signals propagated over fixed line-of-sight paths are subject to randomly distributed fades caused by climatic or atmospheric phenomena such as rain showers, temperature inversions and air turbulence[2]. These effects have been the subject of extensive investigation and a great deal of statistical evidence has been accumulated[3,4] as to the probable frequency of occurrence and the depths of fades to be expected under given conditions. While it is probable that the signals received during trials runs were sometimes affected by

atmospheric effects, it would have been very difficult to identify such variations in the presence of other signal fluctuations. It was considered therefore, that the subject was outside the scope of this investigation and consequently, the Report is concerned with forms of fading peculiar to mobile radio links and in particular, to air-to-air links.

In air-to-air communications, the aircraft aerial beam-widths are usually sufficiently wide to permit reception of both the direct ray and a ray reflected off the earth's surface. In these circumstances, the received signal is the vector sum of two components which have a relative phase angle dependent upon the difference in length of the two paths. Relative motion of the aircraft causes a progressive change of path length difference which is observed at the receiver as a cyclic variation of signal strength. The instantaneous frequency of this fading is proportional to the rate of change of path length difference measured in wavelengths per second. It will be appreciated that an essential requirement for this form of fading is that the surface of the earth is sufficiently smooth to support specular reflection.

6.3.1 Ground effect fading at X-band

Theoretical fade frequencies for flights over a perfectly smooth surface (see Fig.7) were calculated mainly as a means of identifying fading patterns recorded during the trials. As some degree of experimental error is inevitable in the determination of the aircraft's height, distance and ground speed; the errors incurred by assuming, for the specified flight pattern, a plane earth surface are of little significance, and this assumption has been made in computing the theoretical curves.

It will be seen from Fig.8 that for a plane earth surface, the path length difference between the direct and the ground reflected ray is:

$$D = (R^2 + 4h_1 h_2)^{\frac{1}{2}} - R \qquad (1)$$

where

D = Path length difference
R = Slant range of aircraft from receiving aerial
h_1 = Height of receiving aerial
h_2 = Height of transmitting aerial.

The fade frequency is then:-

$$F = \frac{1}{\lambda} \cdot \frac{dD}{dt} = \frac{1}{\lambda}\left[R(R^2 + 4h_1 h_2)^{-\frac{1}{2}} - 1\right] \frac{dR}{dt} \qquad (2)$$

where F = fade frequency

λ = wavelength of radio waves

For the particular conditions obtaining, a further simplification can be made, since, as the X-band aerial directivity precludes fading at ranges of less than about four miles, i.e. $R >> h_1 h_2$, then

$$D \simeq \frac{2h_1 h_2}{R} \tag{3}$$

$dr/dt \simeq V$ (the aircraft's ground speed) and

$$F \simeq \frac{2h_1 h_2 V}{R^2 \lambda} \tag{4}$$

Equation (4) expresses the relationship between fade frequency and distance for horizontal motion. The equivalent equation for vertical motion is:-

$$f \simeq \frac{2h_1}{\lambda R} \cdot \frac{dh_2}{dt} \tag{5}$$

While the aircraft is descending between 17 and 20 nm, the fade frequency is the algebraic sum of the two components, i.e. F + f.

Ground reflection coefficients, which govern fading depth, depend largely upon the surface roughness, the nature of the surface material and the polarisation angle of the radio waves. Smooth surface reflection coefficients are higher for horizontal polarisation at all angles of incidence. For this reason, the majority of the trials were restricted to vertically polarised radiation.

Calculations of fade depths at U.H.F. and microwave frequencies which are based upon smooth earth models are often pessimistically high, because in practice, terrain irregularities diminish specular reflection and hence, reduce ground effect fading. For this reason, fading is most severe over calm water and generally insignificant over rough terrain. Starr and Walker[5] have stated that as a rough guide, specular reflection may be expected over water or terrain in which the height of irregularities is less than $\lambda/2\pi\theta$ (where θ is the angle between the ground incident ray and the horizontal). Relating this expression to the specified flight pattern, and assuming irregularities of height 10 inches, specular reflection at X-band would not be significant until the grazing angle had decreased to about 1° (near the end of the flight).

Fig.9 shows the calculated peak-to-peak fading to be expected for flights at X-band over smooth sea-water. The dotted curves assume omni-directional aerial characteristics; the solid curves show the improvement to be expected when assuming a directional aerial of $\pm 2.5^{\circ}$ beamwidth at the -3dB points. The constriction in the dotted envelope between three and four miles is due to the reduction in reflection coefficient at the pseudo-Brewster angle. Beyond this point, the envelope expands smoothly to 17 nm when, as the aircraft commences its descent, the grazing angle decreases at a greater rate and the envelope expands more sharply. This trend is reversed at about 19 nm when divergence (due to earth curvature) decreases the power flux in the indirect ray. It will be seen that an output S/N ratio of about 20 dB is needed under "free-space" conditions to ensure an adequate margin for fading.

6.3.2 <u>Ground effect fading at U.H.F.</u>

Since fading frequency in two-path propagation is inversely proportional to the wavelength of the radio waves, it follows that much less rapid fading is to be expected at U.H.F. than at X-band. Consequently, it becomes feasible to plot to a convenient scale a theoretical curve of signal strength versus distance for a typical run, presenting in the one curve, information on both the frequency and the depth of fading. Such a curve (Fig.10) for a hypothetical flight over perfectly smooth sea-water has been plotted (actually in terms of received power) by the method described by Domb and Pryce[6]. The customary allowance has been made for atmospheric refraction by assuming an effective earth radius of $\frac{4}{3}$ the actual value.

From Fig.10 it is evident that the main characteristics of the fade frequency/distance curve are similar to those of Fig.7, in that the fade rate decreases progressively as the range increases until the 17 nm point is reached when, as the aircraft descends, there is a sudden increase. It will be seen that, because the values of the pseudo-Brewster angle are different at U.H.F. and X-band (3.5° and 6.5° respectively) the constriction of the envelope occurs further along the path in Fig.10 as compared with the dotted envelope of Fig.9. As would be expected from the specified aerial characteristics of the two systems fade depths at short and intermediate distances are greater for the U.H.F. signals, although over the last mile or so the minima are slightly less deep.

It is evident, from the Starr and Walker expression quoted in (6.3.1) above, i.e. $h = \lambda/2\pi\theta$, that much larger terrain irregularities would be needed to be as effective at U.H.F. as at X-band in suppressing specular ground reflections. For this reason, there is a greater probability that fading patterns

consistent with interference from ground reflected rays would be observed on the U.H.F. recordings made of over land flights.

6.4 Discrete reflecting objects

Radio waves at U.H.F. and higher frequencies propagated over rough terrain may still be subject to multi-path propagation if there are reflecting objects such as metallic structures sited so as to lie within the beamwidths of both the transmitting and receiving aerials. The process is identical with that described in (6.3.1) above, except that, as the point of reflection is fixed, the fading-frequency curves differ from those of Figs.9 and 10. In fact, it can be shown (see Appendix A) that the fading frequencies are related to the distances of the reflecting object along, and perpendicular to the track.

In view of the fact that, as regards the over land flights, all the recorded fading at X-band and most of the fading at U.H.F. appeared to be caused by reflecting objects, it was considered worthwhile to investigate the sources responsible. Studies of Ordnance Survey Maps together with visual surveys of the paths revealed so many possible sources that it was decided to try a theoretical approach based upon analysis of the recorded signal traces.

It is shown in Appendix A that, assuming uniform horizontal motion of the aircraft and that $\frac{dr}{dt} \simeq V$

$$r \simeq R_1 - \frac{R_2 - R_1}{\sqrt{\frac{f_1}{f_2}} - 1}$$

$$k \simeq \sqrt{\frac{2f_1\lambda}{V}} \cdot \frac{R_2 - R_1}{\sqrt{\frac{f_1}{f_2}} - 1} \ .$$

Where k = Perpendicular distance of the object from the path of the direct ray between the aircraft and the tower.

r = Distance from the tower along the direct ray path to the point of intersection with the perpendicular dropped from the object.

R_1 = Slant range of the aircraft when the fade frequency is f_1.

R_2 = Slant range of the aircraft when the fade frequency is f_2.

V = Velocity of aircraft (horizontal motion is assumed).

Considering only fixed ground based objects, there are two positions, one on each side of the line joining the tower and aircraft at which an object could be located to produce identical fading patterns.

This approach also yielded insufficiently accurate data upon which to make positive identifications. There were two main reasons for this; firstly, the recorded fading patterns were complicated by the presence of components from several reflecting sources received simultaneously, which made accurate determination of instantaneous fade-frequencies difficult. Secondly, air turbulence and pilots height corrections added vertical components to the aircraft's velocity, which gave rise to random variations of the fade-frequencies. The first of these problems could be solved by the use of narrow band audio filters. There appears to be no simple solution to the second problem, but if high values of f_1 and f_2 are chosen, corresponding to points on the path slightly beyond the reflecting object (relative to the tower), the effects of the random vertical components of the aircraft's velocity are minimised.

7 DISCUSSION OF THE RESULTS

7.1 Over sea trials at U.H.F.

The three headings along which the over sea runs were flown are shown in Fig.11. Tracks 335°T and 050°T, of which the former skirts a headland and the latter runs roughly parallel to the coast line, were chosen so as to reveal possible effects of coastal reflections. A total of 24 satisfactory recordings was obtained of which six were for track 030°T, seven for track 335°T and eleven for track 050°T.

Examples of the experimental curves of received power versus distance for each of the three headings are shown in Figs.12, 13 and 14. It will be seen that fade rates are generally in agreement with the theoretical curve of Fig.10. The relationships between fade depths and distance along track also conform reasonably well with the fading envelope of Fig.10 although there were considerable variations between the fade depths recorded on the different headings.

The deepest fading was consistently observed over the last few miles on track 335°T where peak-to-peak fades of 24 dB were recorded. It will be noted that this result is 11 dB greater than the theoretical value for the same distance. Deeper fading than theoretical was also observed on track 050°T. That these results are not confined to one or two freak fades is clear from Fig.15 which compares peak-to-peak fading averaged for all the runs on each heading with the calculated theoretical curve. The particular cause of this effect remains unknown. It was noted previously by E.H. Jones[7] during high level U.H.F. trials but was unexplained. It was decided that the problem could not be pursued to its conclusion on this work programme.

7.2 Over sea trials at X-band

Number of runs on track 030°T:- 9

Number of runs on track 050°T:- 11

Number of runs on track 335°T:- 6

The curves of Figs.16, 17 and 18 show the maximum and minimum values of the X-band received power in every half-mile of runs flown over each of the three over sea paths. Comparing these curves with the theoretical envelope of Fig.9 it will be seen that there is some measure of agreement as regards variation of fade-depth with distance. Important differences are that some fading (generally less than 3dB peak-to-peak) appears at ranges up to 5 nm in the experimental curves and that, on average, peak-to-peak fading at longer distances was less severe than theoretical. This conclusion is confirmed by Fig.15 which compares the average peak-to-peak fading in every mile for all runs on each heading with the theoretical values.

It is considered that aerial tracking errors, slight frequency drifts and receiver aerial polar diagram characteristics accounted for some fading at short range; the reduction in fade-depth below theoretical smooth surface levels at greater ranges was due to surface roughness since, at X-band, the wavelength of the radio waves is not much more than one inch and hence quite small sea waves would drastically reduce specular reflection (see 6.3.2 above).

Referring back, Fig.7 compares the recorded fade frequencies with calculated values for one run and it will be seen that the two curves agree reasonably well in general characteristics. The overall slightly higher values of the experimental frequencies for the level part of the flight was evidently due to errors in estimating aircraft height, speed and distance. Of these, aircraft altitude was the most likely to be in error. Some disparity in the two curves for the descent phase was expected since the aircraft was unable to conform exactly to the theoretical flight pattern.

7.3 Over land trials at U.H.F.

Trials in the Farnborough area were flown over two paths bearing 210°T and 270°T from the Ewshot Receiver Station, which is situated about 3 miles S.W. of Farnborough. The terrain along both paths is gently undulating (Figs.19 and 20) and there are no extensive built-up areas although track 270°T skirts the hangars and administrative buildings of Odiham Airfield. A feature of some significance common to both paths is the belt of woodland of over a mile in width fringing the Ewshot Receiver Station.

The slant-line shaded sections of the contours shown in Figs.19 and 20, indicate the areas of terrain screened from the receiving aerials by intervening prominences. It will be observed that there is more screening on 210°T than 270°T and it is considered that this has a bearing on the results obtained on the two paths.

The much more rugged nature of the terrain on the Aberporth OP21 path is clearly shown in the contour of Fig.21.

Number of runs flown on track 210°T (Farnborough):- 18
Number of runs flown on track 270°T (Farnborough):- 28
Number of runs flown on track 308°T (Aberporth):- 4

In addition 4 runs were made to 40 nm ascending from 500 ft above the receiving aerials to 20000 ft on a heading of 270°T at Farnborough. The results obtained on these tests are discussed separately at the end of this section.

Curves of received power versus distance for flights over each of the paths are shown in Figs.22, 23 and 24. Comparing these curves with those obtained for the over sea flights, it is clear that the over land fading patterns are less obviously attributable to specular ground reflection. It might be considered that, due to the undulations along the path, the fade-frequencies would rise and fall as the ground reflection point advanced with the aircraft's motion. While this must partly account for the irregular nature of the fading patterns, it should be noted that because of the relatively low height of the ground receiving aerials, the point of reflection would not progress more than about one mile until the aircraft had begun its descent. It is considered therefore that much of the fading was caused by reflections from other sources, i.e. the discrete reflecting objects discussed in Section 6.4

From the examples presented, it is seen that depths of fading differed considerably on the three paths. In fact, despite some disparity between the results obtained for repeat runs over the same paths, the main features of the recorded signal traces were much more characteristic of the path flown. Thus, for the two paths near Farnborough, much less fading was observed on 210°T. It will be seen in the next sub-section that a similar result was obtained at X-band where all significant fading could be attributed to reflection from metallic structures. This correlation between the results obtained at the two frequencies extends also to the concurrence of fading at various points along the path, from which it is concluded that the same reflecting objects were often responsible for the effects observed. It would appear therefore that either there are more reflecting objects along 270°T than 210°T or that more

potential reflecting sources are screened on 210°T by intervening prominences. In fact, it is probable that both explanations apply.

As would be expected from the hilly nature of the terrain at Aberporth, very little evidence of specular ground reflection was observed during flights based on OP21. Nevertheless, distinct fading patterns are evident on the experimental curves of Fig.24. It is concluded that some of the metallic structures (e.g. a transformer "farm" and pylons) which were visually observed were responsible for this fading.

7.4 Over-land trials at X-band

Number of runs on track 210°T (Farnborough):- 23
Number of runs on track 270°T (Farnborough):- 27
Number of runs on track 308°T (Aberporth):- 4

The envelopes of Figs.25, 26 and 27 show the peak-to-peak fading at X-band for runs flown over each of the three paths. No effects of specular ground reflection were discernible on any of the recordings and all the fading patterns appear to have stemmed from reflections from metallic structures. However, fading depths rarely exceeded 6 dB on any flight.

One conclusion drawn as a result of flying several runs on nominally the same path is that the fading characteristics are significantly modified by quite minor departures from the prescribed track. It is assumed that aerial directivity is, to a large extent, responsible for this effect.

As mentioned in 7.3 above, severity of fading was much greater on 270°T at Farnborough as compared with 210°T. Since all the fading was caused by reflections from metallic structures, it follows that more of the objects lay within the beam of the ground receiving aerial on 270°T. It is believed that the Odiham hangars were responsible for some of the observed fading; other likely sources were noted, such as pylons and metal-roofed factories and farm buildings.

When fading is caused by discrete reflecting objects, the highest possible fade frequency, assuming a hemi-isotropic aircraft aerial is V/λ, see Appendix A. Thus for an aircraft ground speed of 210 kn, the highest fade frequency at X-band is about 3500 c/s. Thereafter the frequency falls rapidly at first and then more slowly. Fade-frequency characteristics of this form were in fact observed although when the frequency was high, the depth of fading was invariably low. It is believed that massive metallic structures could, in certain configurations, be the cause of fairly severe high frequency fading, although in an air-to-air circuit, the effects would necessarily be transitory.

The results of the 40 nm runs to 20000 ft are shown in Figs.28, 29 and 30. The height/distance curve being plotted from aircraft altimeter readings.

The envelope of peak-to-peak fading at U.H.F., Fig.28 shows that the fading never exceeded 6 dB. At maximum range the received mean power level was -88 dBm. Figs.29 and 30 compare the difference between results obtained using the 9 inch and 18 inch dishes. With the 9 inch dish the fade depth never exceeded 6 dB peak-to-peak, but due to the decrease in aerial gain, the received power at maximum range was considered marginal. However, by using the higher gain aerial, with greater directivity the fading was only 3 dB peak-to-peak in the worst case.

It is considered that the X-band system with a high directivity aerial is the most suitable. Comparison of U.H.F. and X-band using a 9 inch dish shows great similarity both in depth of fade and received power.

8 CONCLUSIONS

Fade rates at X-band for the over sea flights varied from about 3 c/s to 0.3 c/s, corresponding to path lengths of between 5 and 17 nm. At ranges shorter than 5 nm, fading was insignificant; between 17 and 20 nm the fade frequency increased to about 1.5 c/s due to the aircraft's descent. Much less rapid fading was observed at U.H.F., the frequencies varying between 0.5 c/s at 1 nm and about one fade per minute at 17 nm. The predicted increase in fade rate was observed at both signal frequencies during the descent phase. These results accorded quite well with the calculated fade-frequency curves.

Fading depths at U.H.F. over sea often exceeded the theoretical values (calculated on the basis of a $\frac{4}{3}$ earth radius and using the published information on sea-water reflection coefficients). At X-band, fading was less severe than theoretical and it is considered that this could be attributed to surface roughness. Typical results at U.H.F. were 6-12 dB peak-to-peak during the first 10 nm and 10 dB to 20 dB between 10 and 20 nm. As stated above, fading at X-band was insignificant for the first 5 nm due to aerial directivity; was generally less than 6 dB peak-to-peak between 5 and 10 nm and from 6 dB to 18 dB between 15 and 20 nm.

Some fading patterns were recorded at both signal frequencies during over land flights, but it is evident from analysis of the results that discrete reflecting objects, e.g. pylons, gas-holders, etc were mainly responsible, particularly at X-band. On average, fading was less severe than observed during over sea flights, but varied considerably on the three paths, presumably as a result of the density and disposition of the reflecting objects. The worst

fading over land, occurred consistently on the Farnborough 270°T path where peak-to-peak fades at U.H.F. of up to 16 dB were recorded. The maximum peak-to-peak values at X-band were 4 dB.

A very wide range of fade frequencies was observed during the over land flights. Thus, at X-band some very rapid but relatively shallow fading of up to 3000 c/s was observed at several points along each of the paths but especially noticeable on Farnborough 270°T. It is conceivable that more massive metallic structures could cause rapid and severe fading although in a missile to aircraft link the duration of such phenomena would be short.

The results of the trials indicate that X-band offers advantages over U.H.F. in terms of reduced fading over land and over sea and less prolonged outages. The directivity and high front to back ratio obtainable with microwave aerials would also be advantageous in relation to E.C.M., other factors such as cost and installation problems have not been considered.

Appendix A

DOPPLER-BEAT INTERFERENCE CAUSED BY DISCRETE REFLECTING OBJECTS

In this appendix it is shown that for the conditions obtaining in the X-band experiment, fairly simple expressions for the co-ordinates of a reflecting object relative to the receiving point can be derived in terms of known or measurable quantities. The particular conditions referred to above stem from the directional characteristics of the receiving and transmitting aerials which limits the position of reflecting objects to a strip of terrain, about one mile wide, straddling symmetrically the aircraft track. The reflecting objects must also be between the aircraft and the receiving aerial and because of the directivity and tracking (in elevation) angles of the receiving aerial, be at least three miles from the base of the aerial tower.

Under these conditions, it is evident that

$$R \gg h_T$$

where R is slant range

h_T is aircraft height,

and

$$\frac{dR}{dt} \simeq V$$

where V is aircraft ground speed.

The configuration of tower, reflecting object and aircraft, are shown in Fig.1(a). The aircraft, at height h_T is assumed to be flying horizontally at a true ground speed V and at an instantaneous slant range $R = (r + y)$.

The distance of the reflecting object O from the tower T is z and its instantaneous distance from the aircraft A is x.

The perpendicular distance of the object from the path of the direct ray (OP) is k and r is the distance along the path of the direct ray to the point P.

Expressions will now be derived for r and k in terms of known and measured quantities. It will be obvious from Fig.1(a) that if r and k are known, b and d (the co-ordinates of the object relative to the tower) are easily determined. It should be noted that the equations are accurate only for the conditions that $y^2 \gg k^2$. This implies in practice that $y \nless 2$ nm.

Referring to Fig.1(a) it will be seen that the direct ray follows the path AT and the indirect ray AOT.

The fade-frequency results from the continuous variation in path length difference J, and is given by

$$f = \frac{1}{\lambda} \cdot \frac{dJ}{dt} \qquad (1)$$

$$f = \frac{1}{\lambda}\left(\frac{dy}{dt} - \frac{dx}{dt}\right) \qquad (2)$$

In AOT, Fig.1:-

$$x = (y^2 + k^2)^{\frac{1}{2}} .$$

If $y^2 >> k^2$

$$x = y\left(1 + \frac{1}{2}\frac{k^2}{y^2}\right)$$

$$\frac{dx}{dy} = 1 - \frac{k^2}{2y^2} . \qquad (3)$$

Then

$$\frac{dx}{dt} = \frac{dx}{dy} \cdot \frac{dy}{dt}$$

from (2)

$$f = \frac{1}{\lambda} \cdot \frac{dy}{dt}\left(1 - \frac{dx}{dy}\right) \qquad (4)$$

when $R >> h_T$, $\frac{dy}{dt} \simeq V$, the aircraft's ground speed.

$$f = \frac{V}{\lambda}\left[1 - \left(1 - \frac{k^2}{2y^2}\right)\right]$$

$$= \frac{Vk^2}{2\lambda y^2} . \qquad (5)$$

Taking values of f_1 at R_1 and f_2 at R_2 and substituting $(R-r)$ for y:-

Then

$$f_1 = \frac{k^2V}{2\lambda(R_1 - r)^2}$$

and

$$f_2 = \frac{k^2V}{2\lambda(R_2 - r)^2}$$

Therefore

$$2f_1(R_1 - r)^2 = 2f_2(R_2 - r)^2 \ .$$

Therefore

$$(R_1 - r) = \sqrt{\frac{f_2}{f_1}}\,(R_2 - r) \ .$$

Therefore

$$r = \frac{\left(R_1 - R_2\sqrt{\frac{f_2}{f_1}}\right)}{\left(1 - \sqrt{\frac{f_2}{f_1}}\right)} \ .$$

This re-arranges to

$$r = R_1 - \frac{(R_2 - R_1)}{\sqrt{\frac{f_1}{f_2}} - 1} \qquad (6)$$

then since

$$f_1 = \frac{k^2 V}{2\lambda(R_1 - r)^2}$$

$$k^2 = 2f_1 \frac{\lambda}{V} (R_1 - r)^2 \ .$$

Therefore

$$k = \sqrt{2f_1\frac{\lambda}{V}}\,(R_1 - r)$$

now from equation (6) and since $y = (R_1 - r)$ then

$$k = \sqrt{2f_1 \frac{\lambda}{V}}\ \frac{(R_2 - R_1)}{\sqrt{\frac{f_1}{f_2}} - 1} \ . \qquad (7)$$

The position of a reflecting object '0' can be determined from the co-ordinates 'r' and 'k', see Fig.1(a).

Assuming a known constant horizontal motion of the aircraft and the wave-length of the transmitted frequency then equations (6) and (7) derived above can be used to obtain these co-ordinates providing that two values of fade frequency f_1 and f_2 at distances R_1 and R_2, along the track, can be extracted from the recorded experimental results.

Considering Fig. 1(b)

$$x^2 = y^2 + k^2$$

differentiating

$$2x \frac{dx}{dt} = 2y \frac{dy}{dt} + 2k \frac{dk}{dt} .$$

Therefore

$$\frac{dx}{dt} = \frac{dy}{dt} \cdot \frac{y}{x} + \frac{dk}{dt} \cdot \frac{k}{x}$$

now since

$$\frac{dJ}{dt} = \frac{dy}{dt} - \frac{dx}{dt}$$

then

$$\frac{dJ}{dt} = \frac{dy}{dt} - \left(\frac{y}{x} \cdot \frac{dy}{dt} + \frac{k}{x} \cdot \frac{dk}{dt}\right)$$

$$= \frac{dy}{dt}\left(1 - \frac{y}{x}\right) - \frac{k}{x} \cdot \frac{dk}{dt} . \qquad (8)$$

Examining equation (8) for the case where $R >> h_T$ and considering the components $\frac{k}{x} \cdot \frac{dk}{dt}$, it is seen that for a steady decrease in their value due to a steady change in aircraft range or height these components are unimportant, but random variations in aircraft height $\left(\frac{dh_T}{dt}\right)$ due to air turbulence are important to path length difference.

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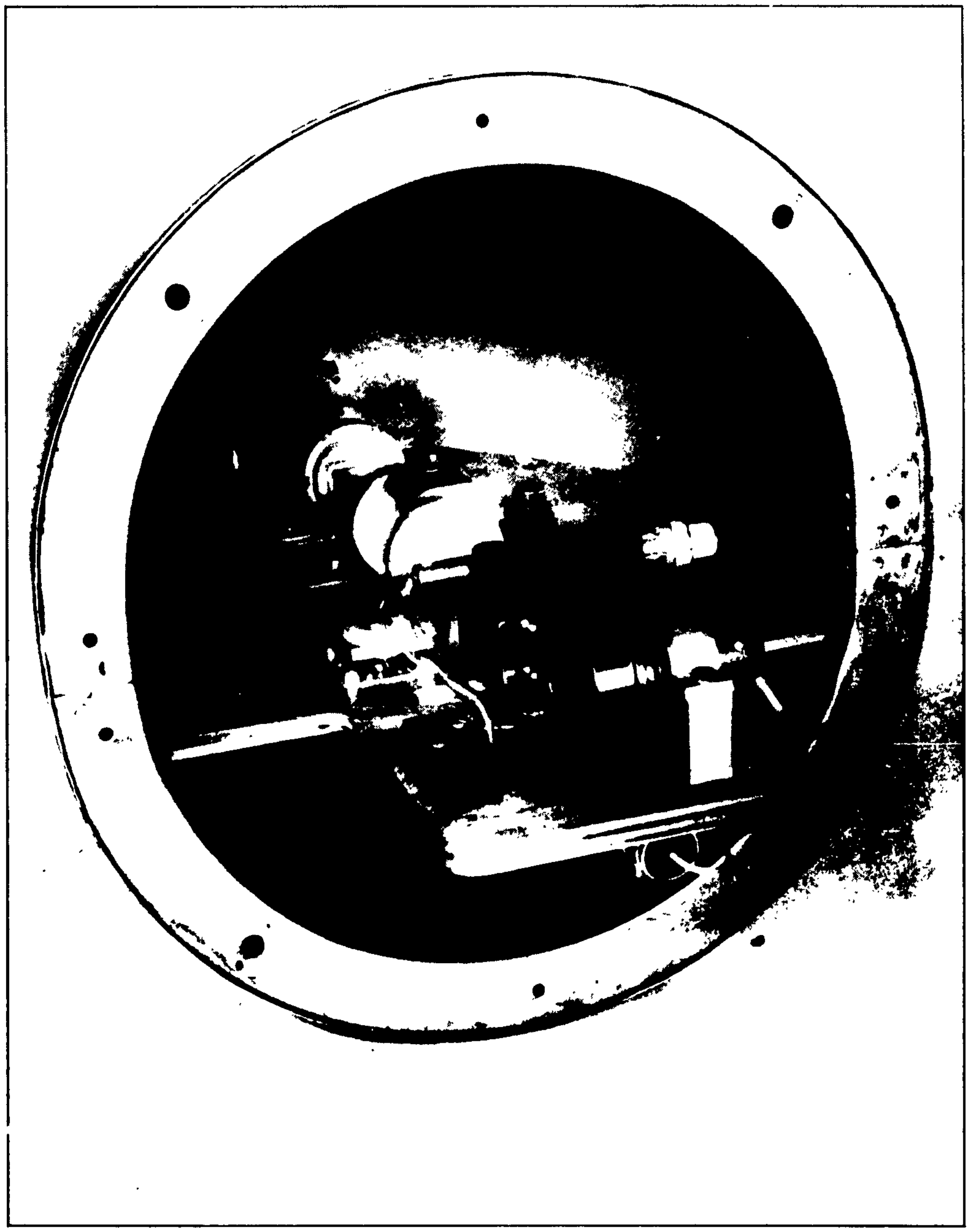

Fig.1. X—Band transmitter

Fig.2

Neg. No. C490

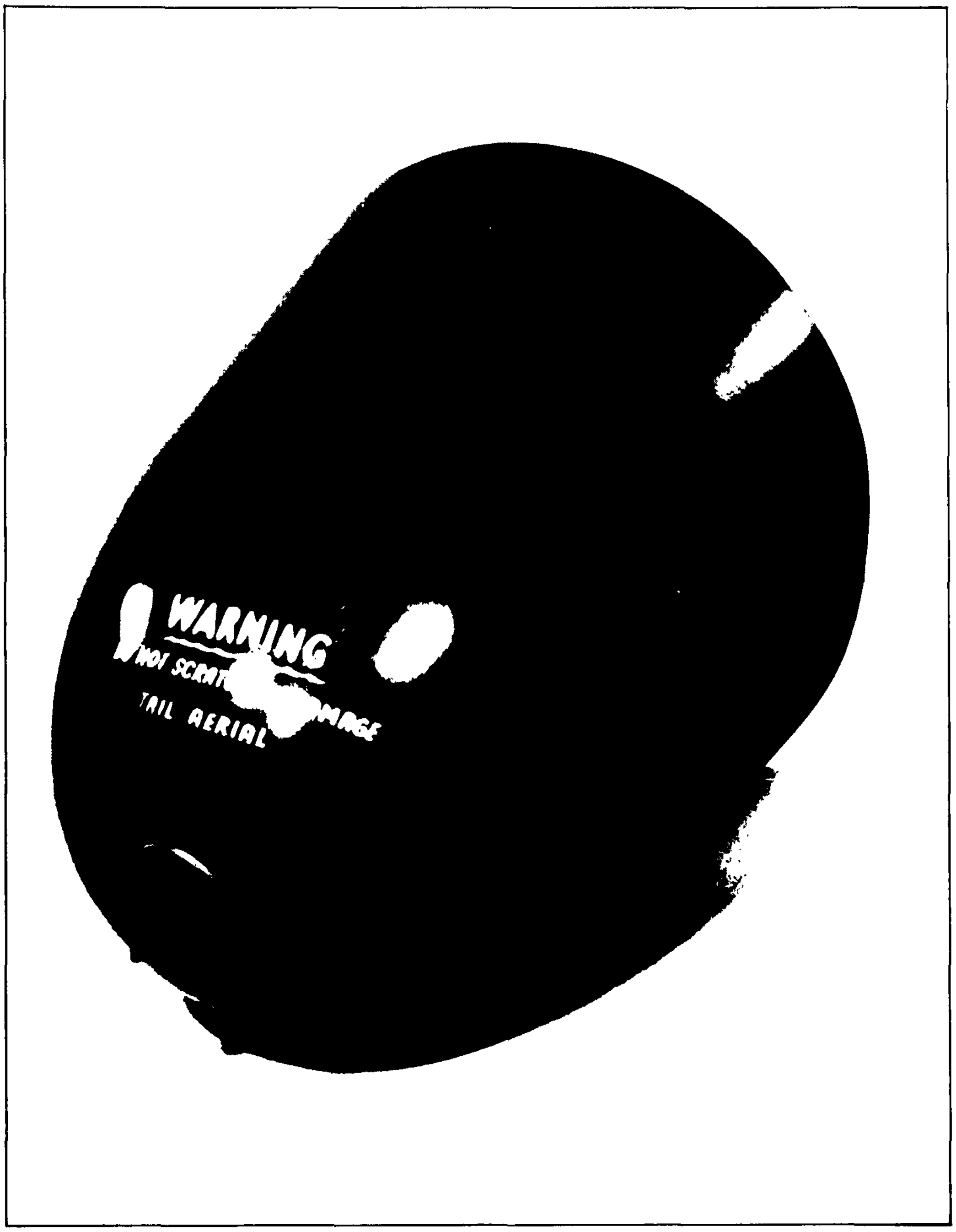

Fig.2. Tapered waveguide aerial

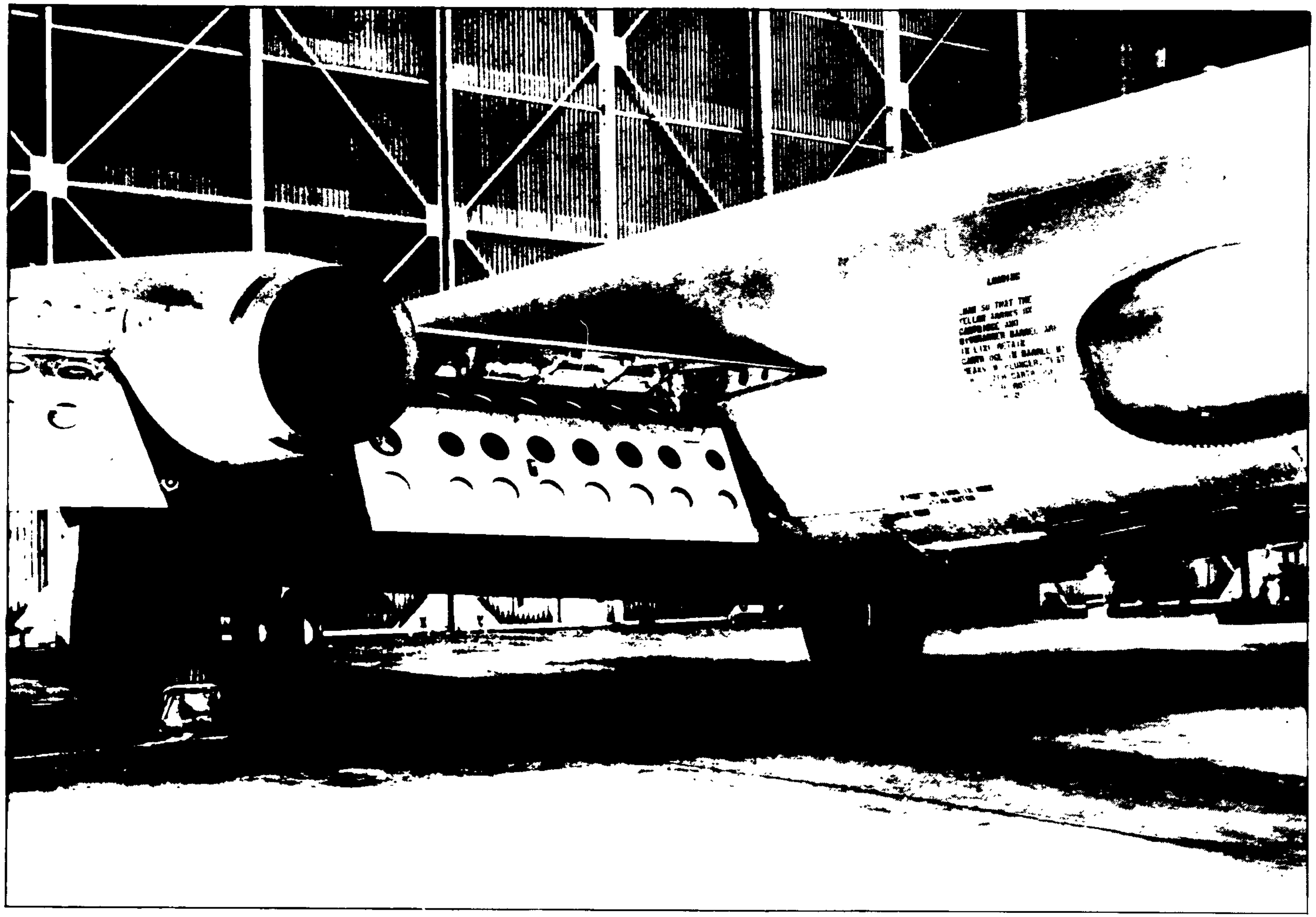

Fig.3. U.H.F. airborne aerial

Fig.4

Neg. No. C492

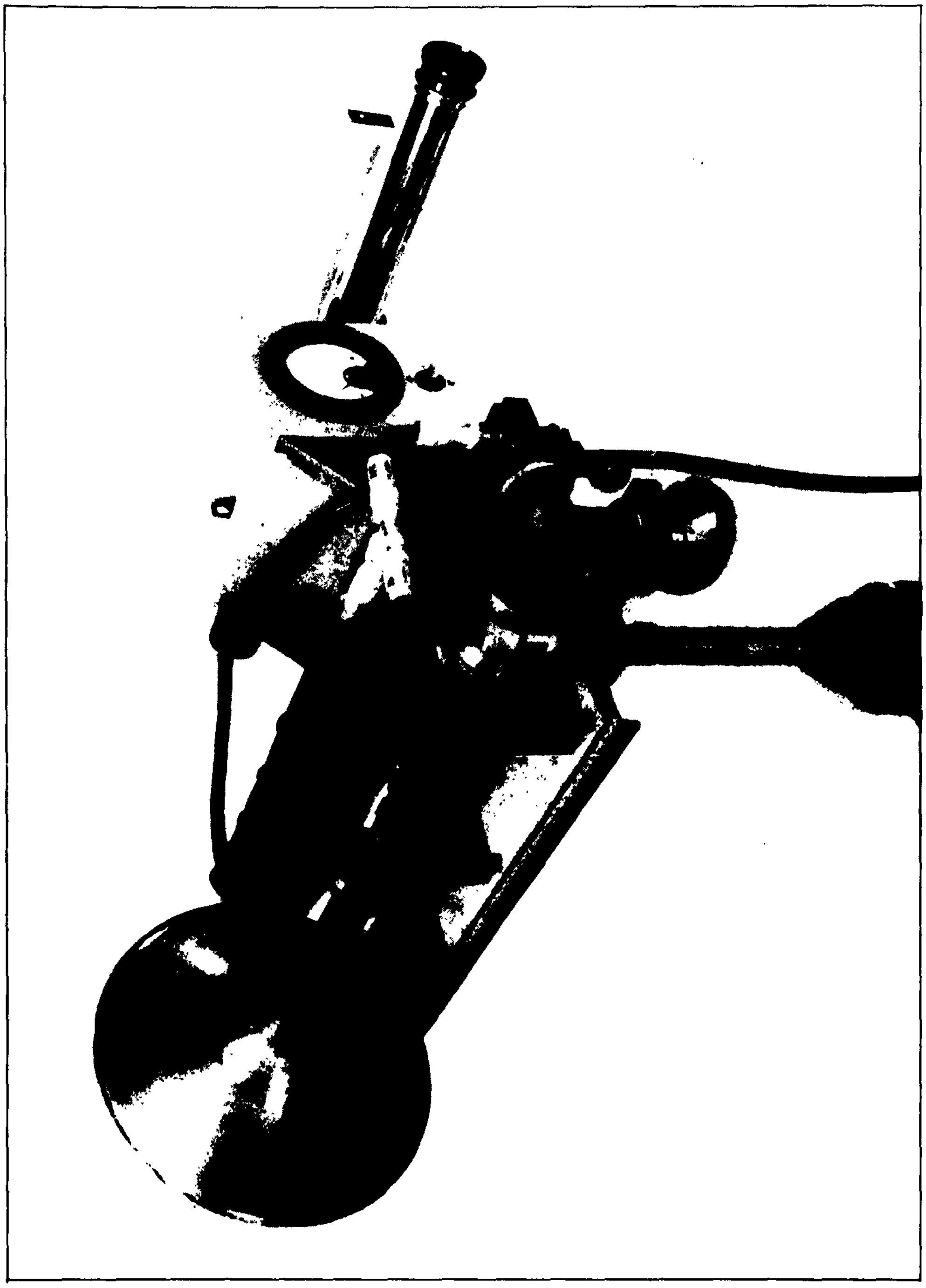

Fig.4. X—Band receiver aerial assembly

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Fig.5

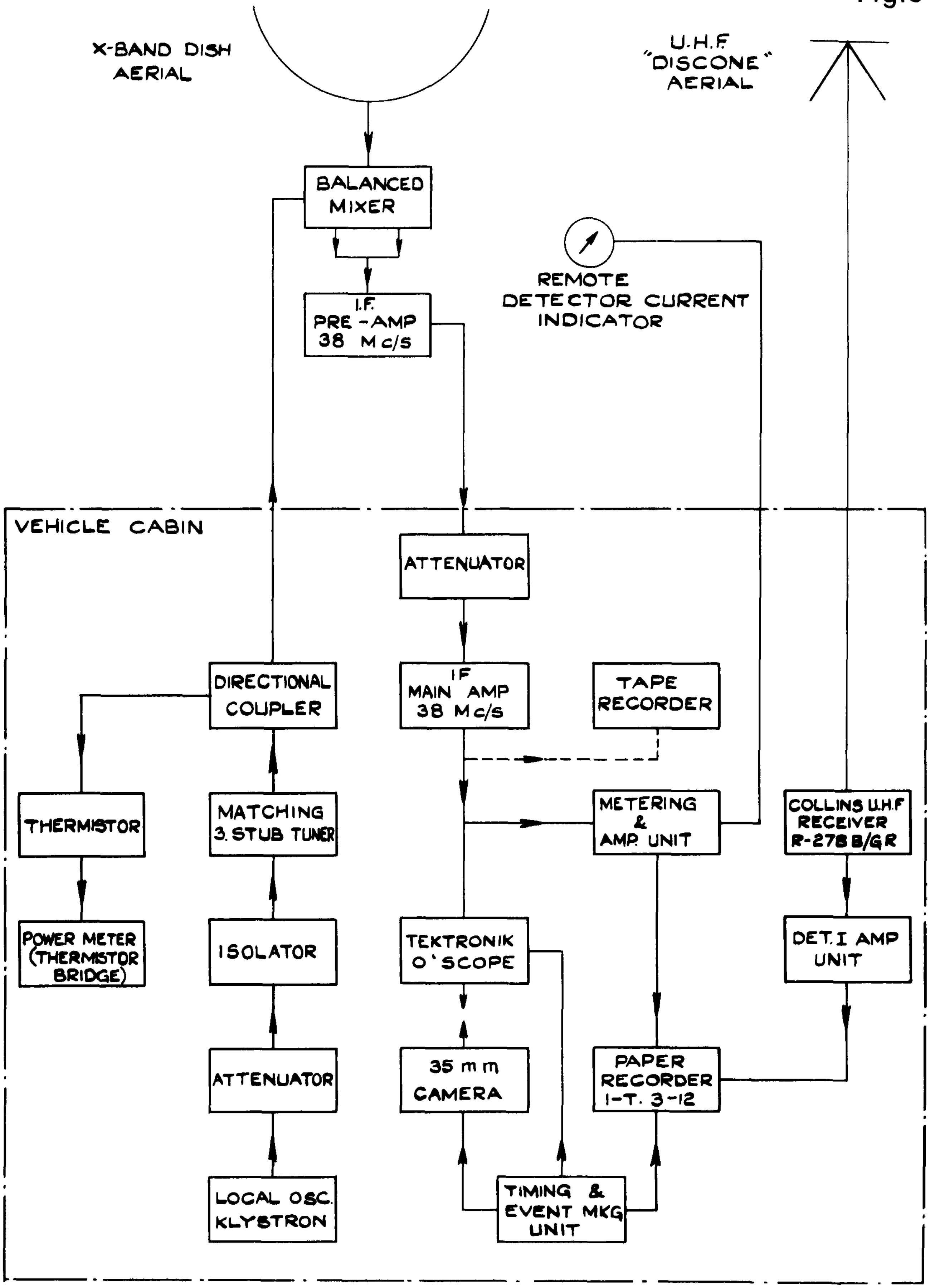


FIG.5 BLOCK SCHEMATIC OF EXPERIMENTAL GROUND STATION INSTALLATION

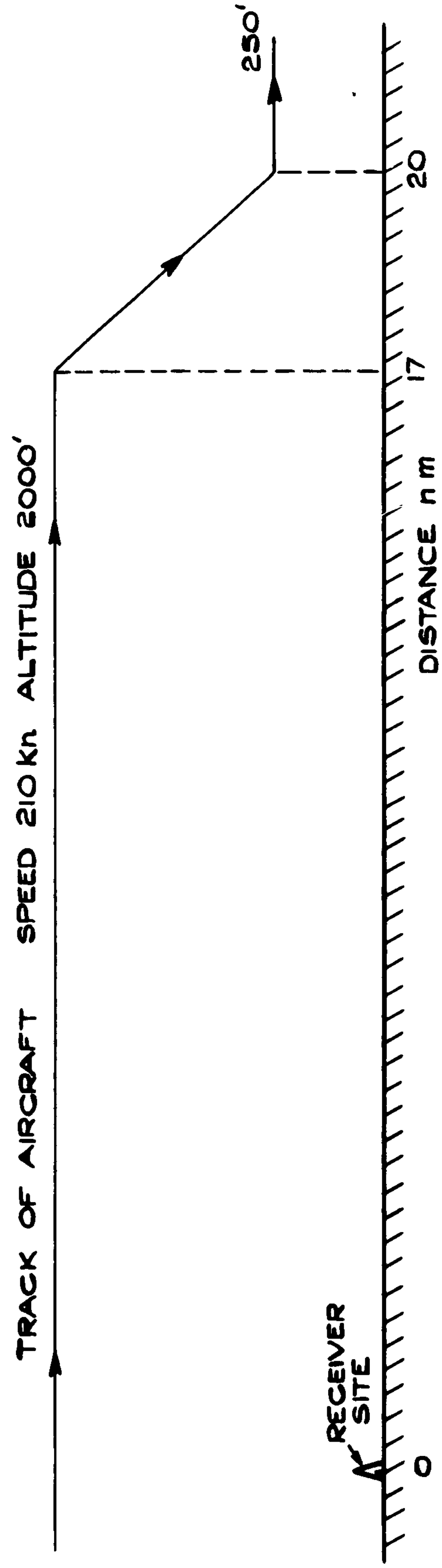


FIG. 6 PROFILE OF AIRCRAFT FLIGHT PATTERN

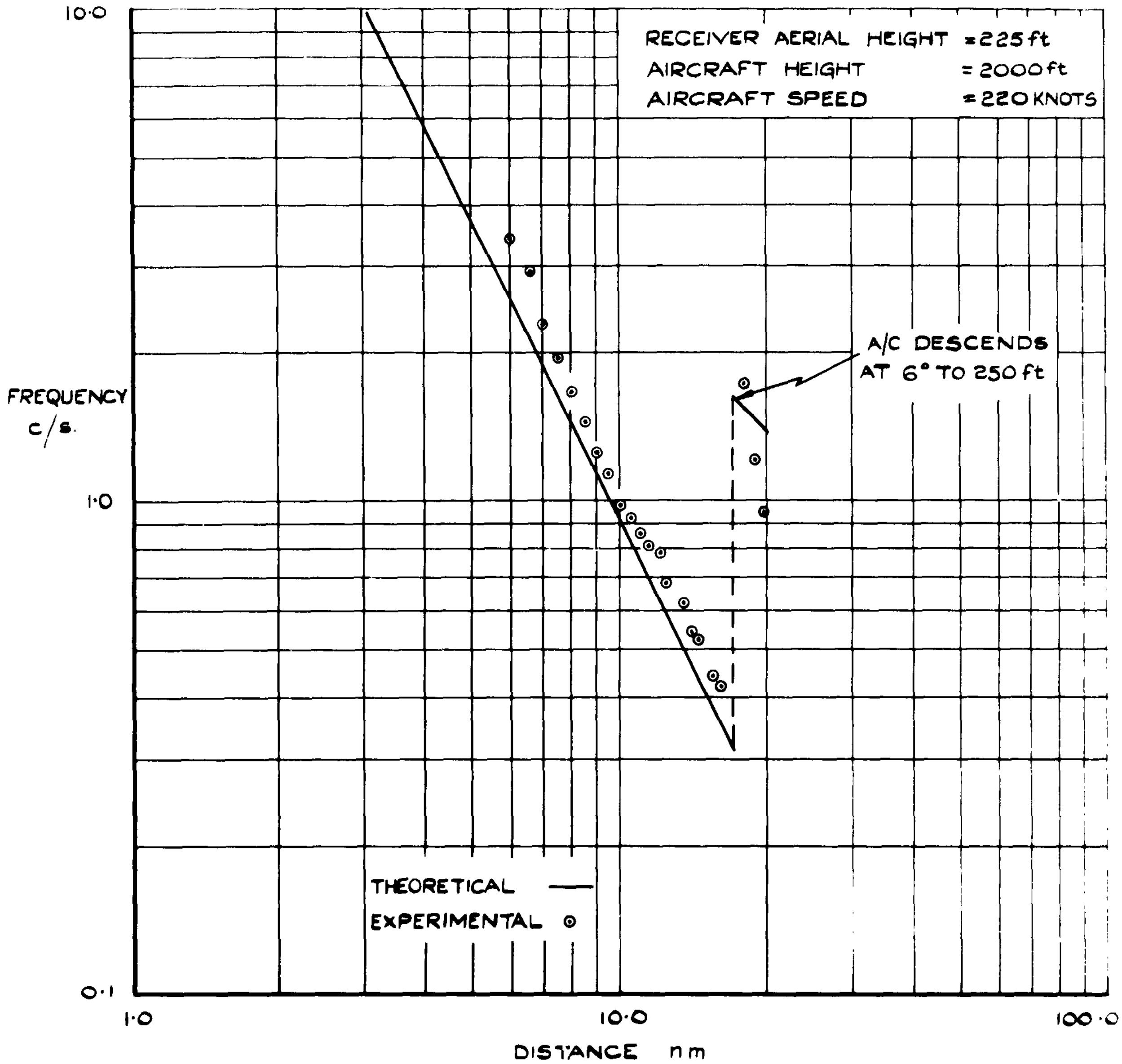
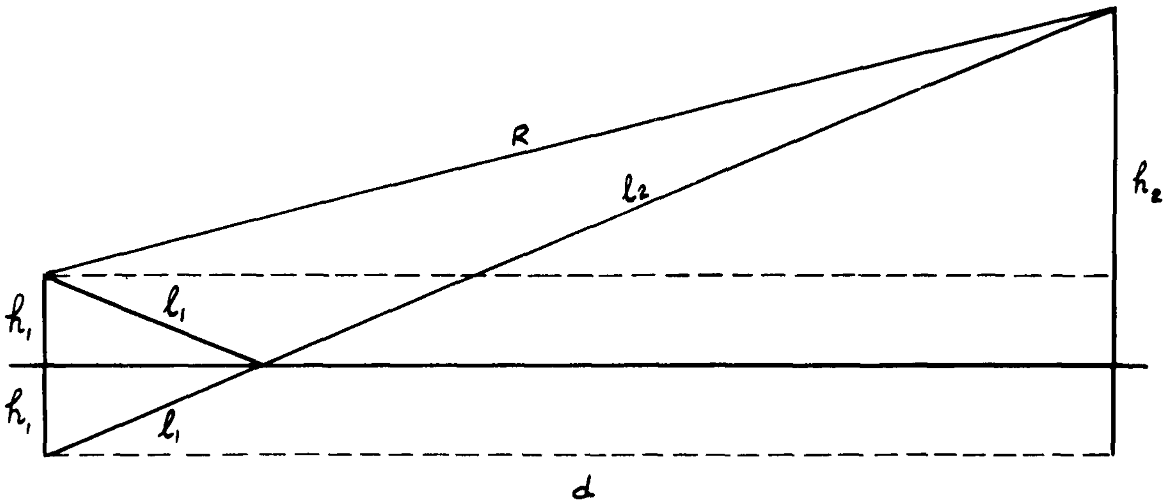


FIG.7 FADING FREQUENCY VERSUS DISTANCE FOR FLIGHT OVER SMOOTH SURFACE AT X-BAND



LET, h_1 = HEIGHT OF RECEIVING AERIAL
h_2 = HEIGHT OF TRANSMITTING AERIAL
R = PATH LENGTH OF DIRECT RAY
$(\ell_1+\ell_2)$ = PATH LENGTH OF REFLECTED RAY
D = PATH LENGTH DIFFERENCE

IT CAN BE SEEN THAT $D = (\ell_1+\ell_2) - R$

TO DERIVE AN EXPRESSION FOR D IN TERMS OF h AND R :-

$$R^2 = (h_2 - h_1)^2 + d^2 \qquad \text{———— (1)}$$

$$(\ell_1+\ell_2)^2 = (h_2+h_1)^2 + d^2 \qquad \text{———— (2)}$$

FROM (1) & (2) $$(\ell_1+\ell_2)^2 - R^2 = 4\,h_2\,h_1$$

$$\therefore (\ell_1+\ell_2)^2 = 4h_2\,h_1 + R^2$$

$$\therefore (\ell_1+\ell_2) = (4h_2\,h_1 + R^2)^{\frac{1}{2}}$$

NOW $$(\ell_1+\ell_2) - R = (4h_2\,h_1 + h^2)^{\frac{1}{2}} - R$$

$$\therefore D = (4h_2 h_1 + R^2)^{\frac{1}{2}} - R$$

FIG.8 GEOMETRY OF DIRECT AND GROUND REFLECTED RAY OVER PLANE SURFACE

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Fig.9

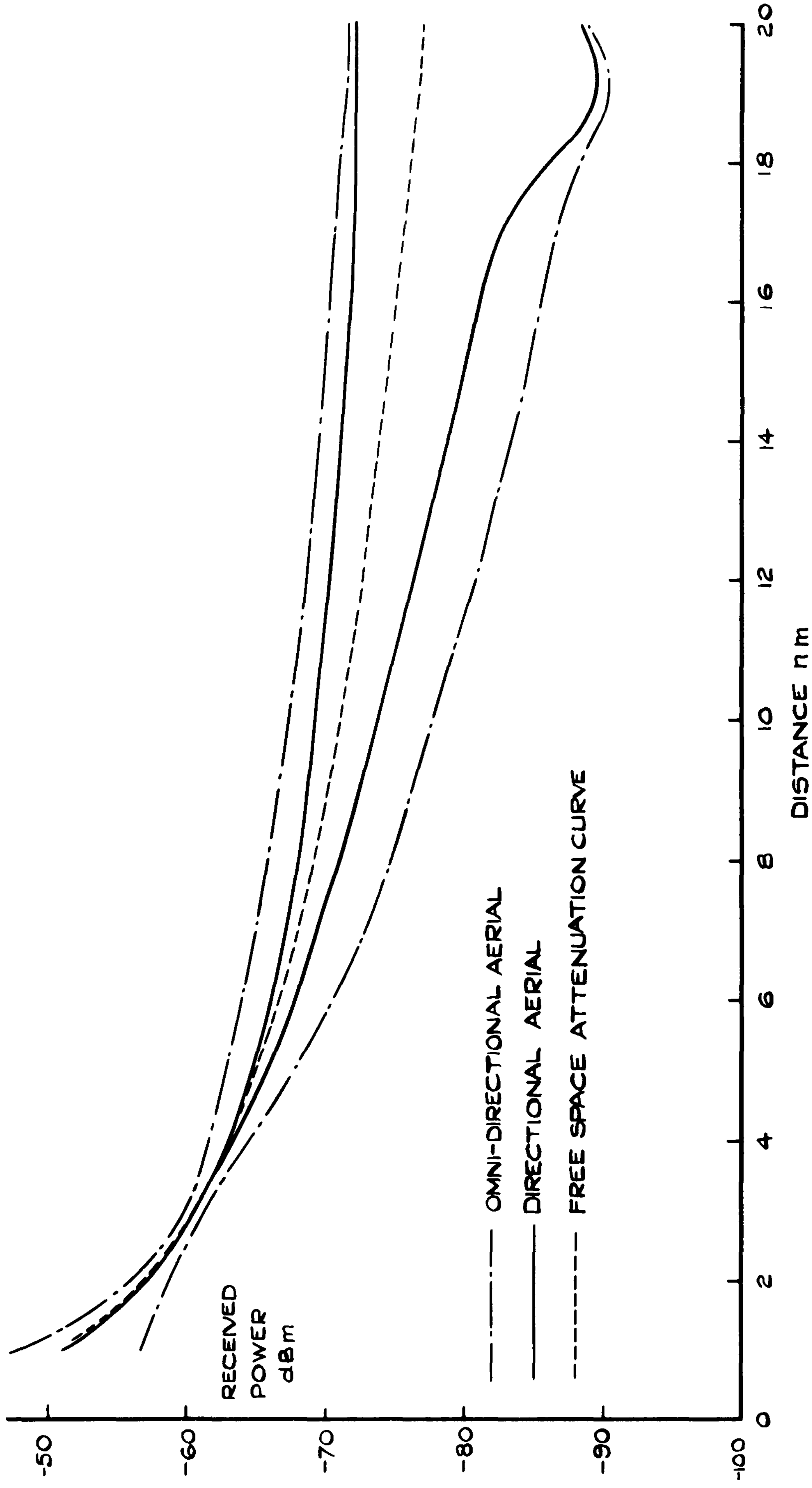


FIG. 9 THEORETICAL ENVELOPES OF PEAK TO PEAK FADING FOR X-BAND FLIGHT OVER SMOOTH SEA WATER

Fig.10

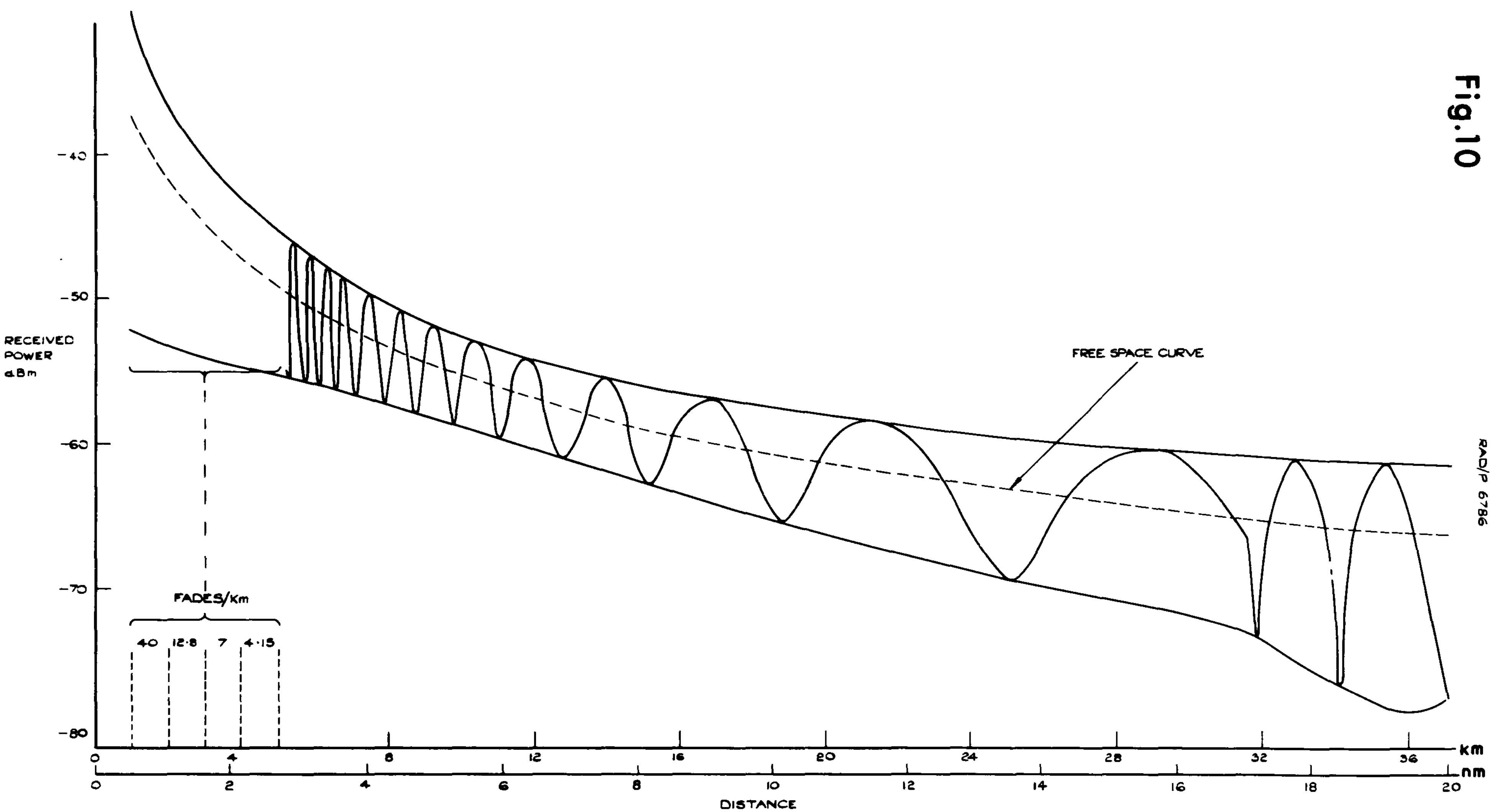


FIG.10 THEORETICAL FADING PATTERN AT U.H.F. (300 Mc/s) FOR FLIGHT OVER SMOOTH SEA WATER

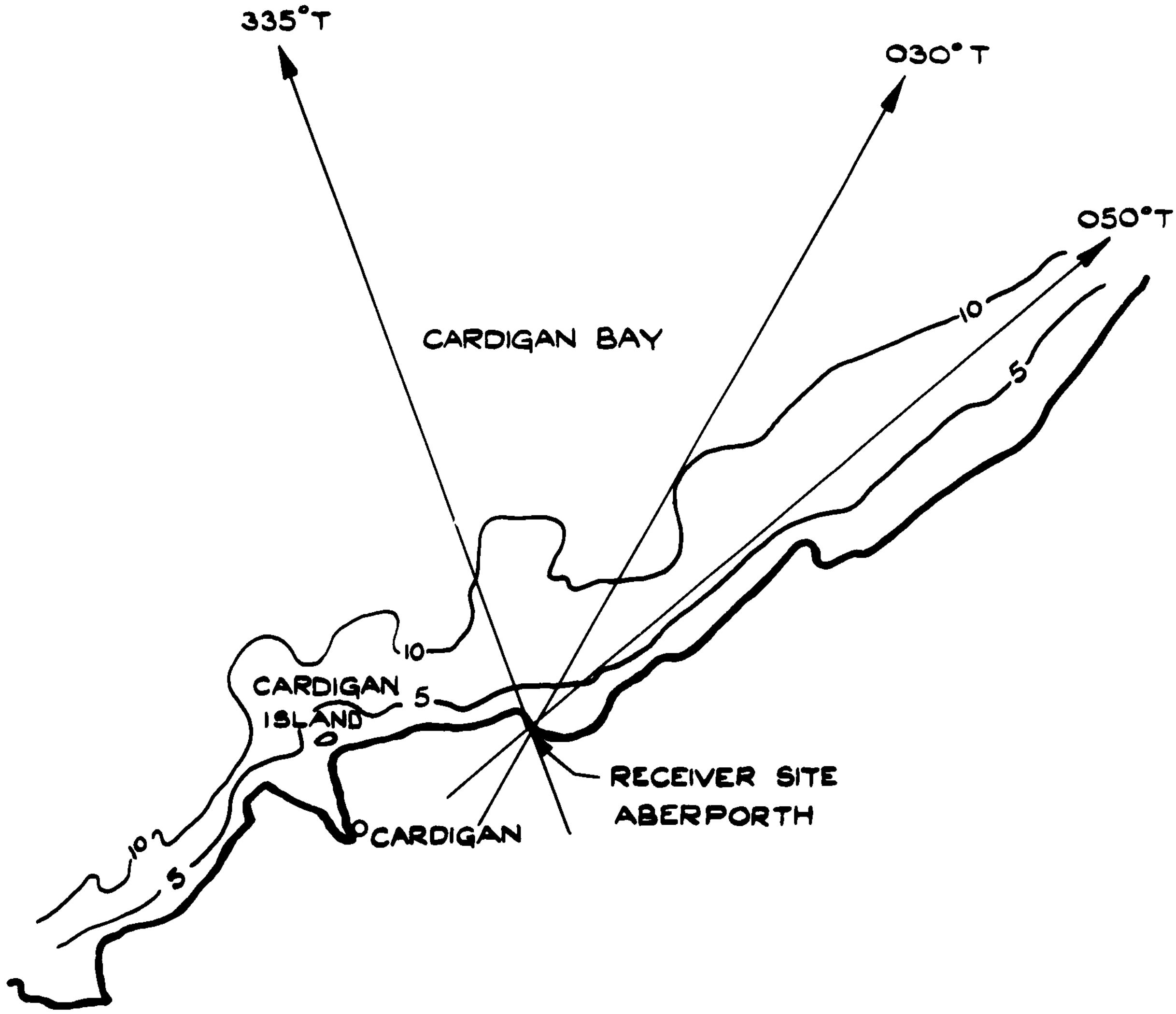


FIG.11 SKETCH MAP SHOWING THE THREE HEADINGS ON WHICH OVER SEA RUNS WERE MADE

Fig.12

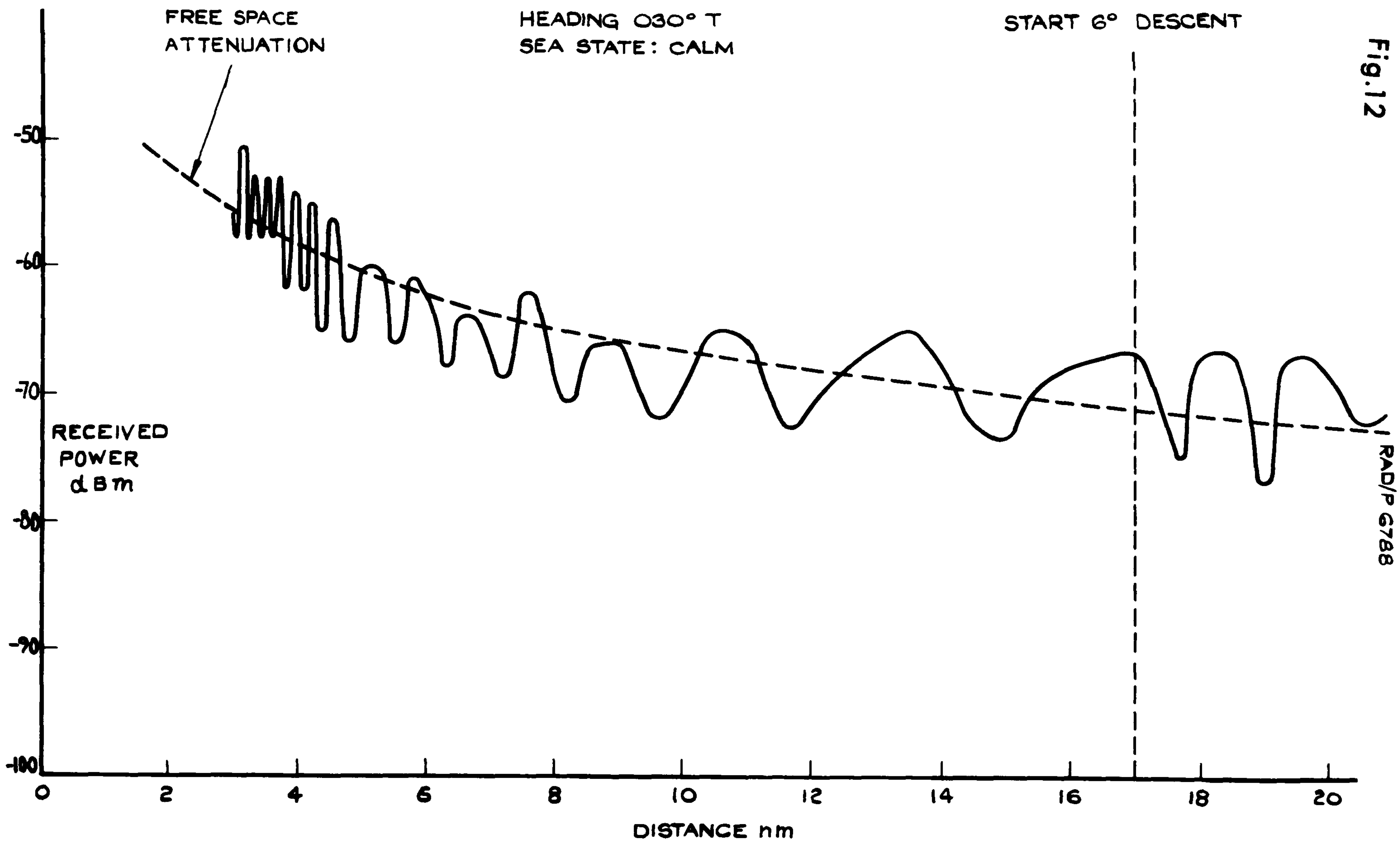


FIG.12 RECORDED FADING PATTERN AT 300 Mc/s FOR FLIGHT OVER SEA WATER HEADING 030° T

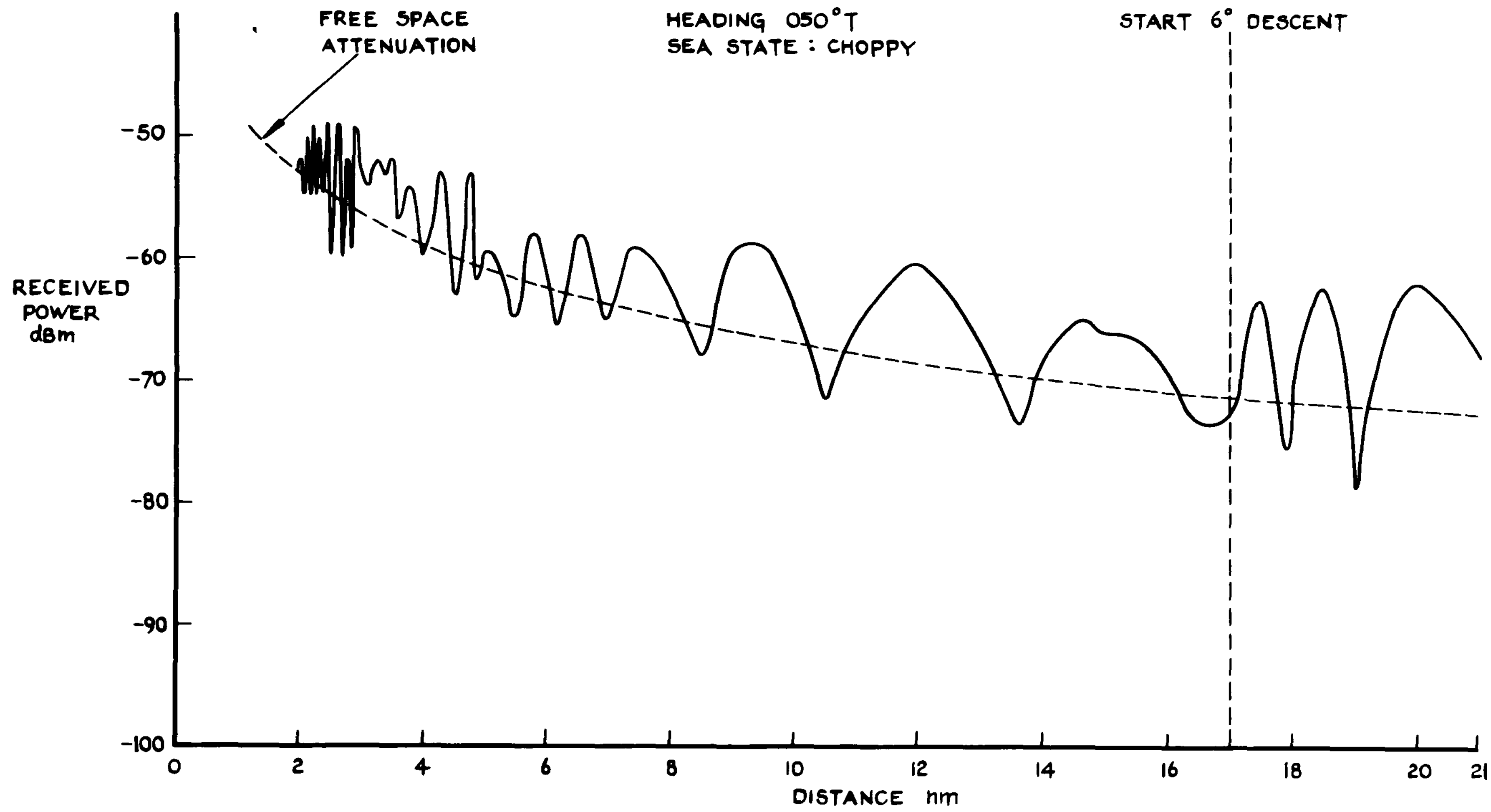


FIG.13 RECORDED FADING PATTERN AT 300Mc/s FOR FLIGHT OVER SEA WATER HEADING 050°T

Fig.14

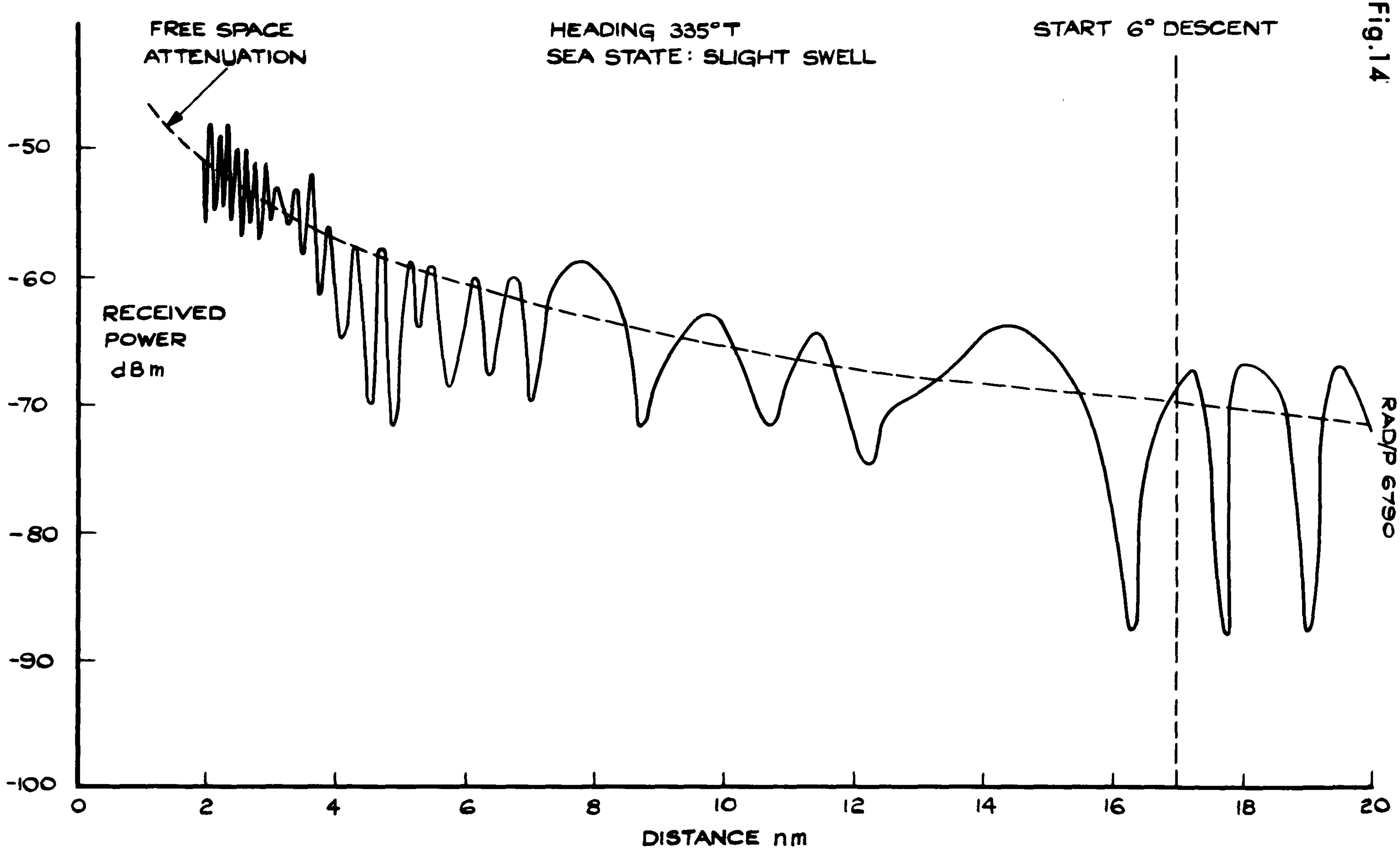
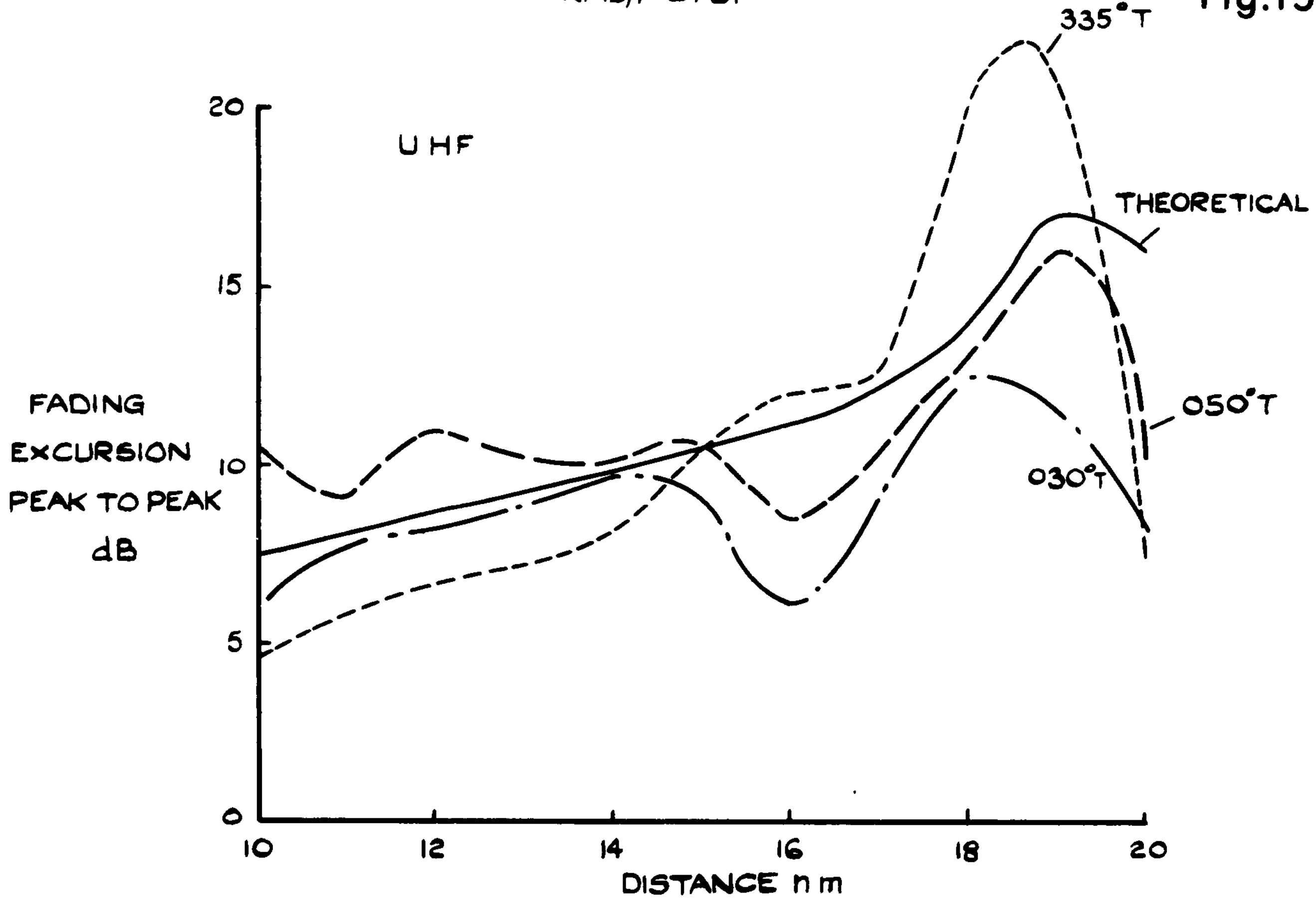


FIG. 14 RECORDED FADING PATTERN AT 300 Mc/s FOR FLIGHT OVER SEA WATER HEADING 335°T



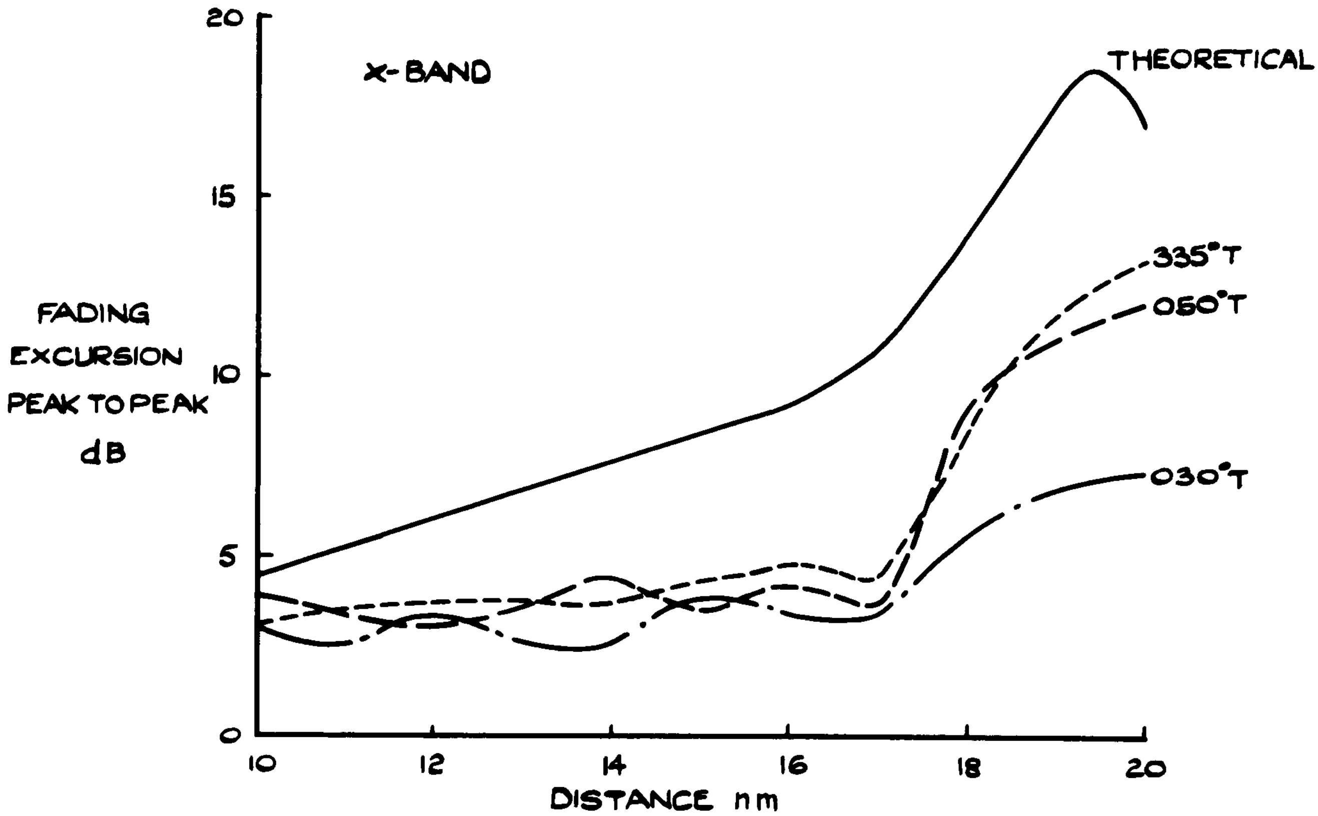


FIG. 15 PEAK TO PEAK FADING AT U.H.F. AND X-BAND OVER LAST 10 nm COMPARED WITH THEORETICAL. CURVES AVERAGED OVER ALL RUNS ON EACH HEADING

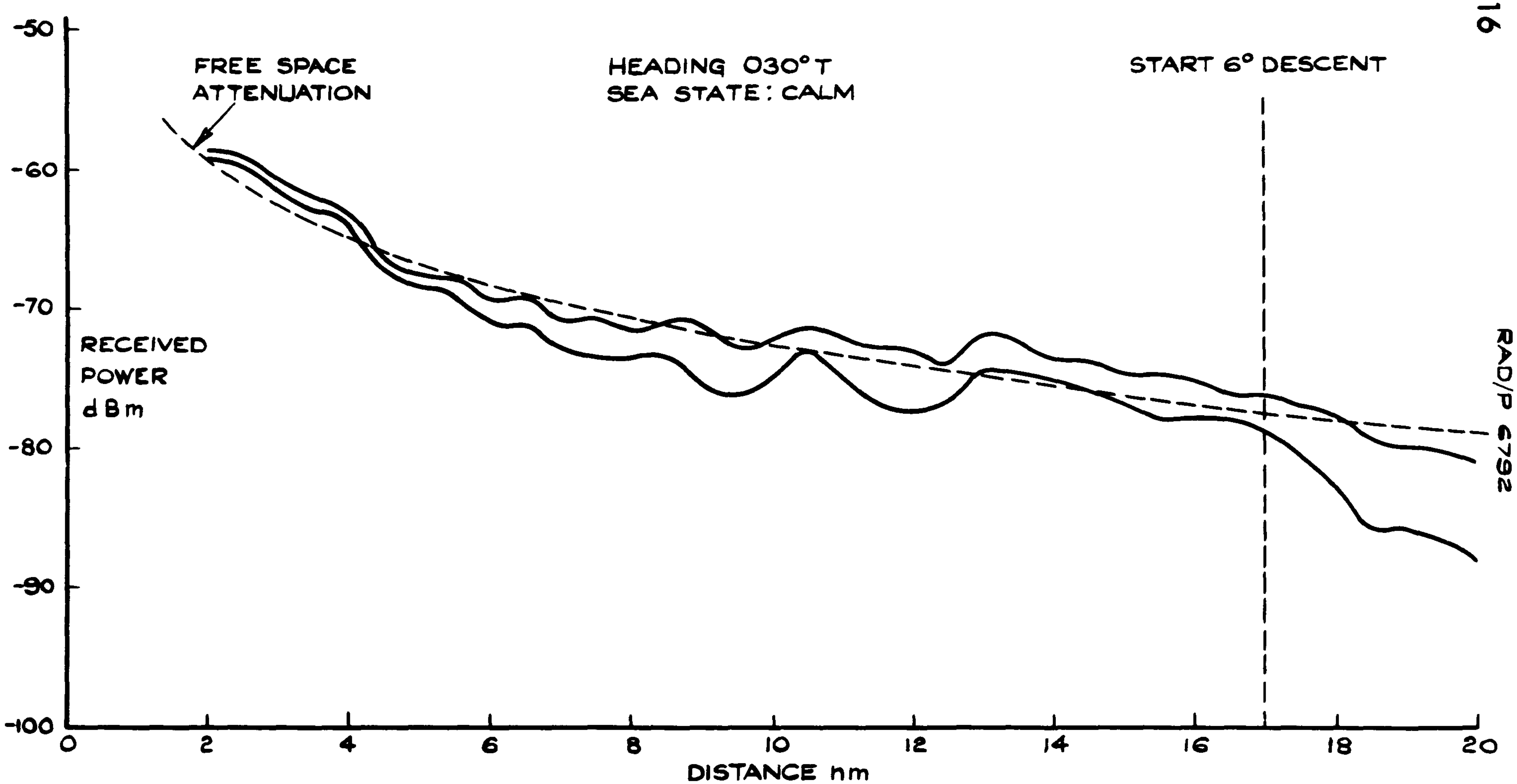


FIG. 16 ENVELOPE OF PEAK TO PEAK FADING AT X-BAND FOR FLIGHT OVER SEA WATER HEADING O30° T.

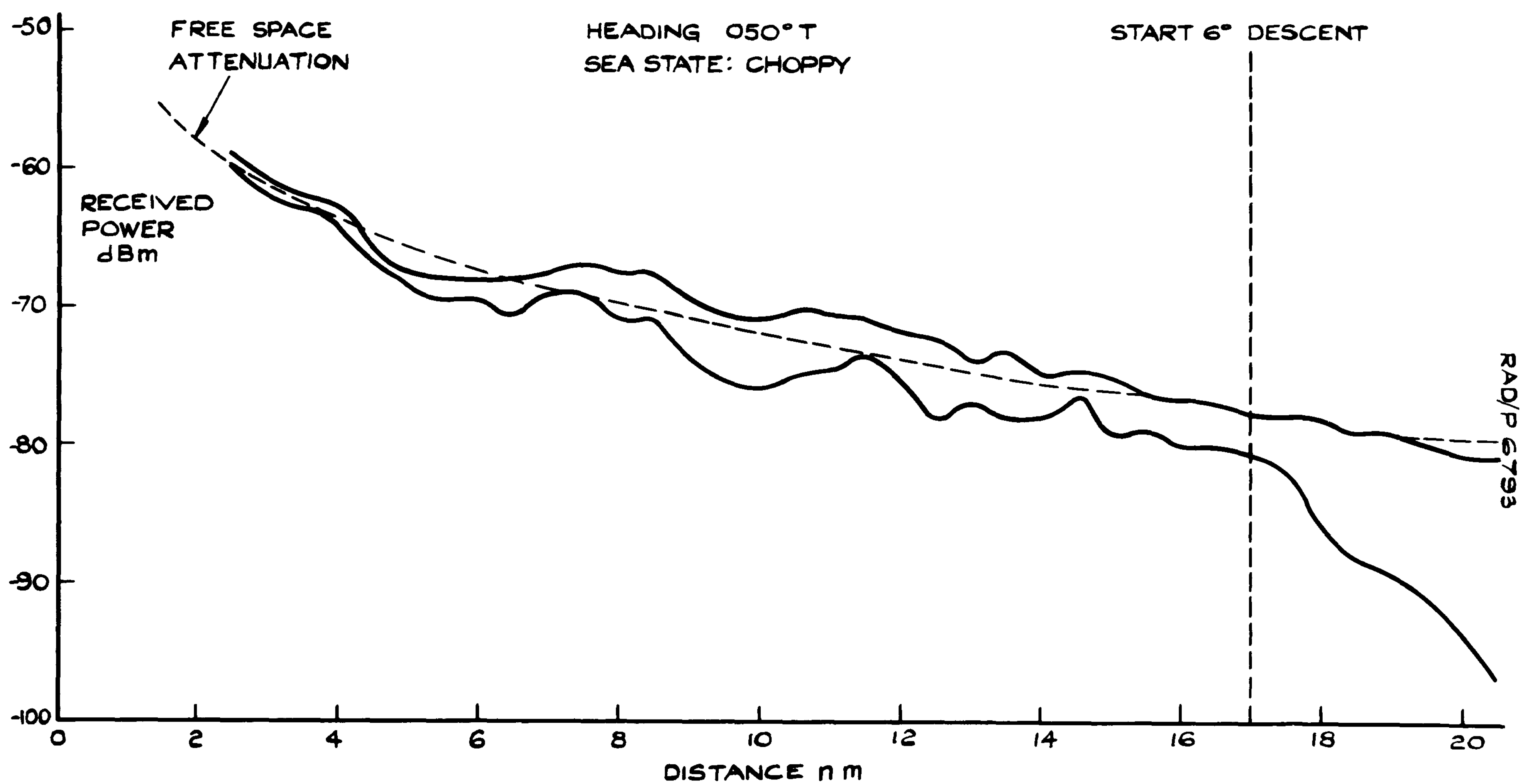


FIG. 17 ENVELOPE OF PEAK TO PEAK FADING AT X-BAND FOR FLIGHT OVER SEA WATER HEADING 050° T

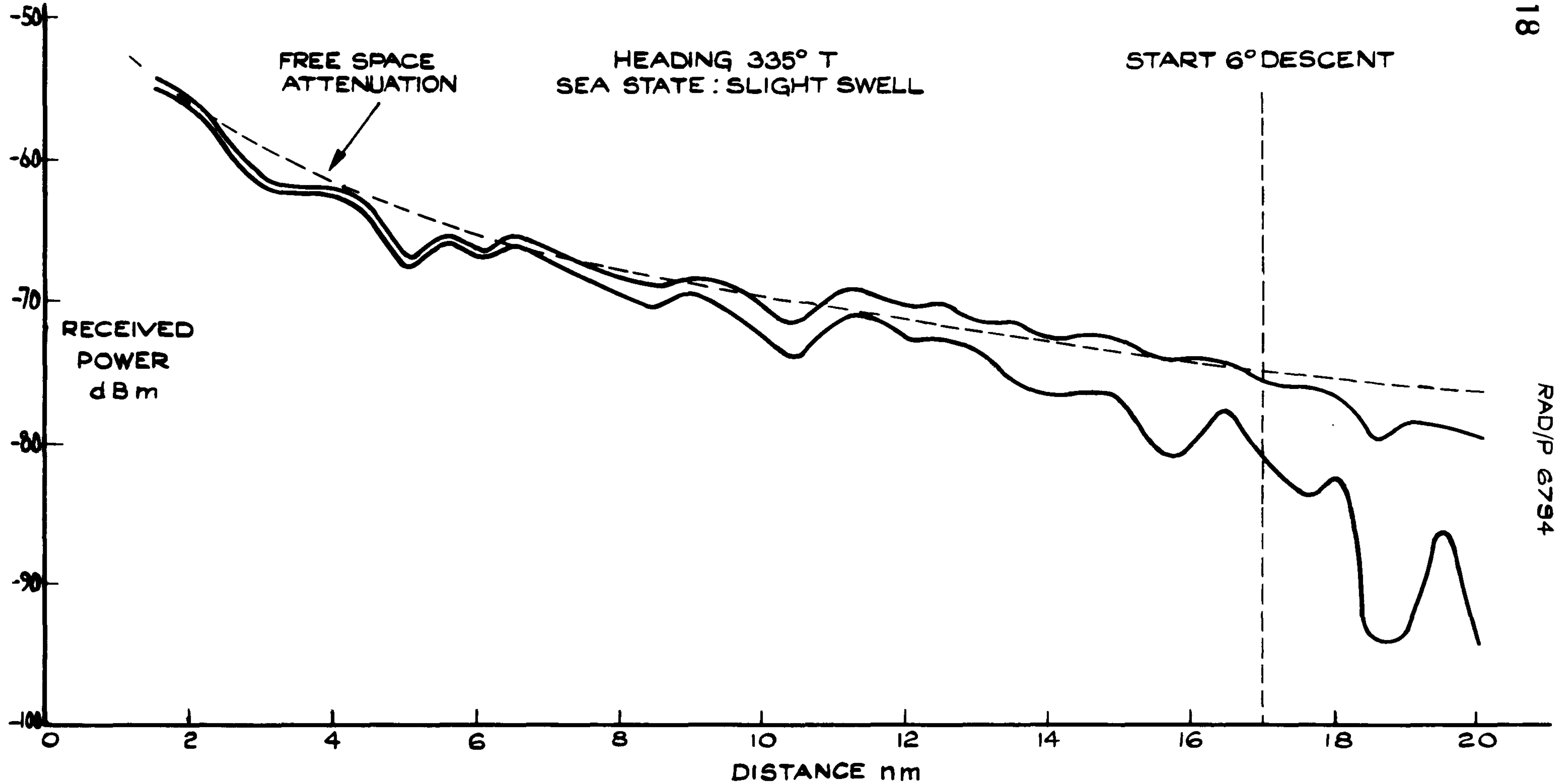


FIG.18 ENVELOPE OF PEAK TO PEAK FADING AT X-BAND FOR FLIGHT OVER SEA WATER
HEADING 335° T

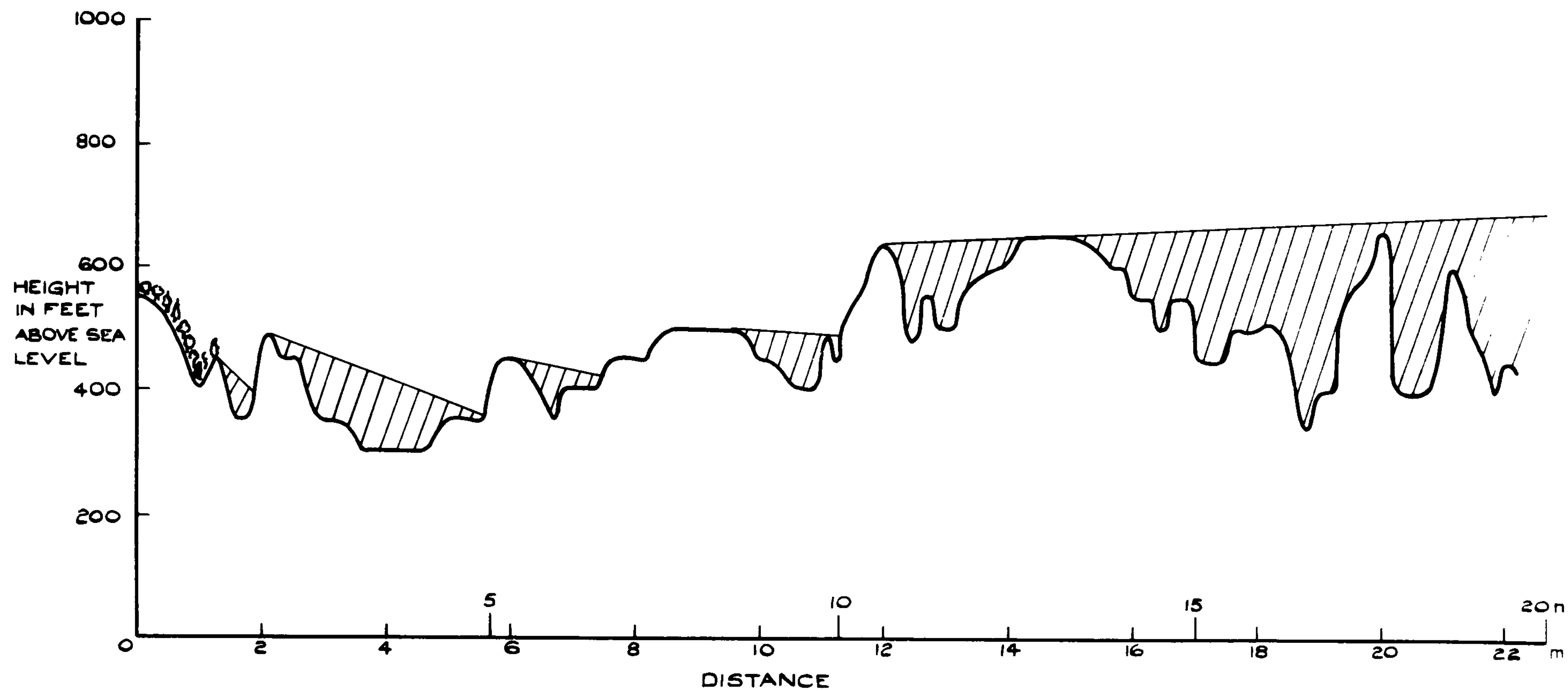


FIG. 19 PROFILE OF TERRAIN ON HEADING 210° T FROM EWSHOT RECEIVING STATION

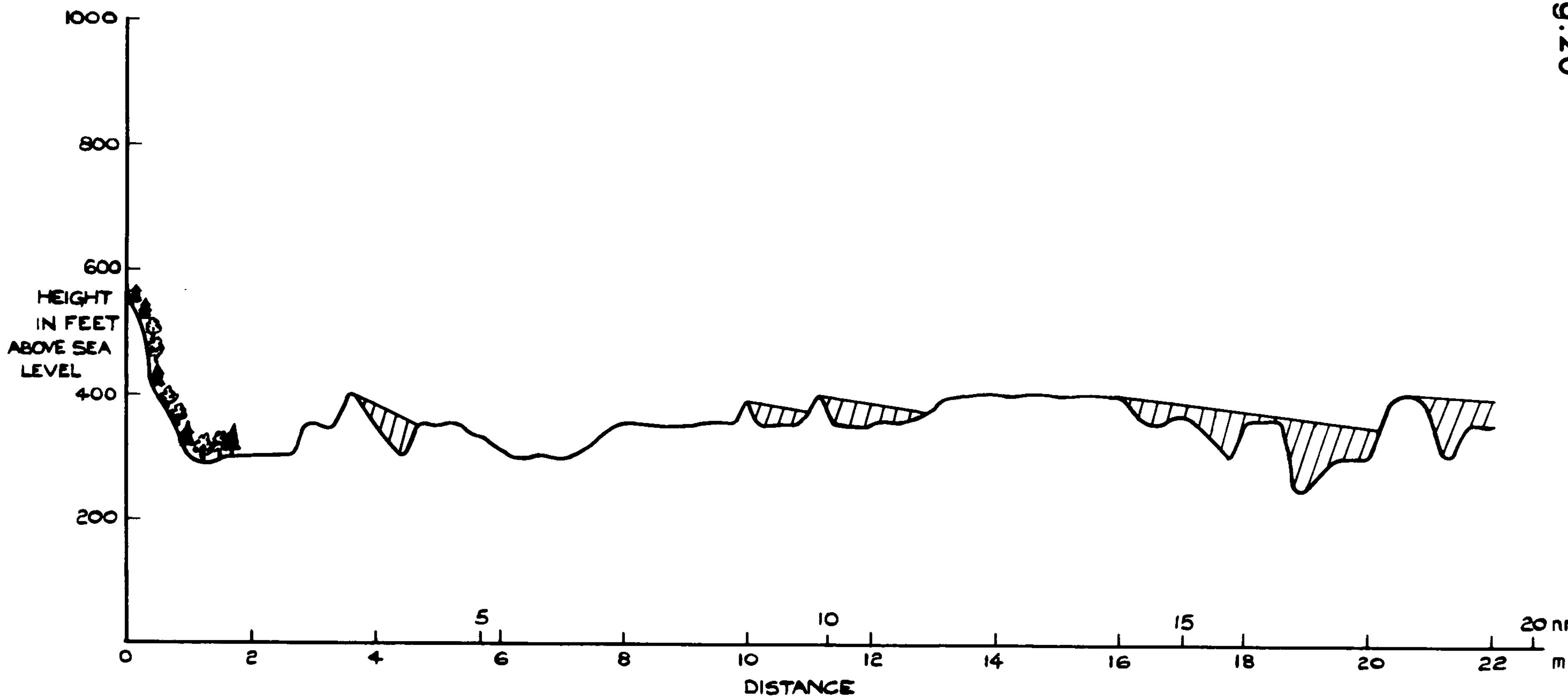


FIG.20 PROFILE OF TERRAIN ON HEADING 270°T FROM EWSHOT RECEIVING STATION

Fig. 21

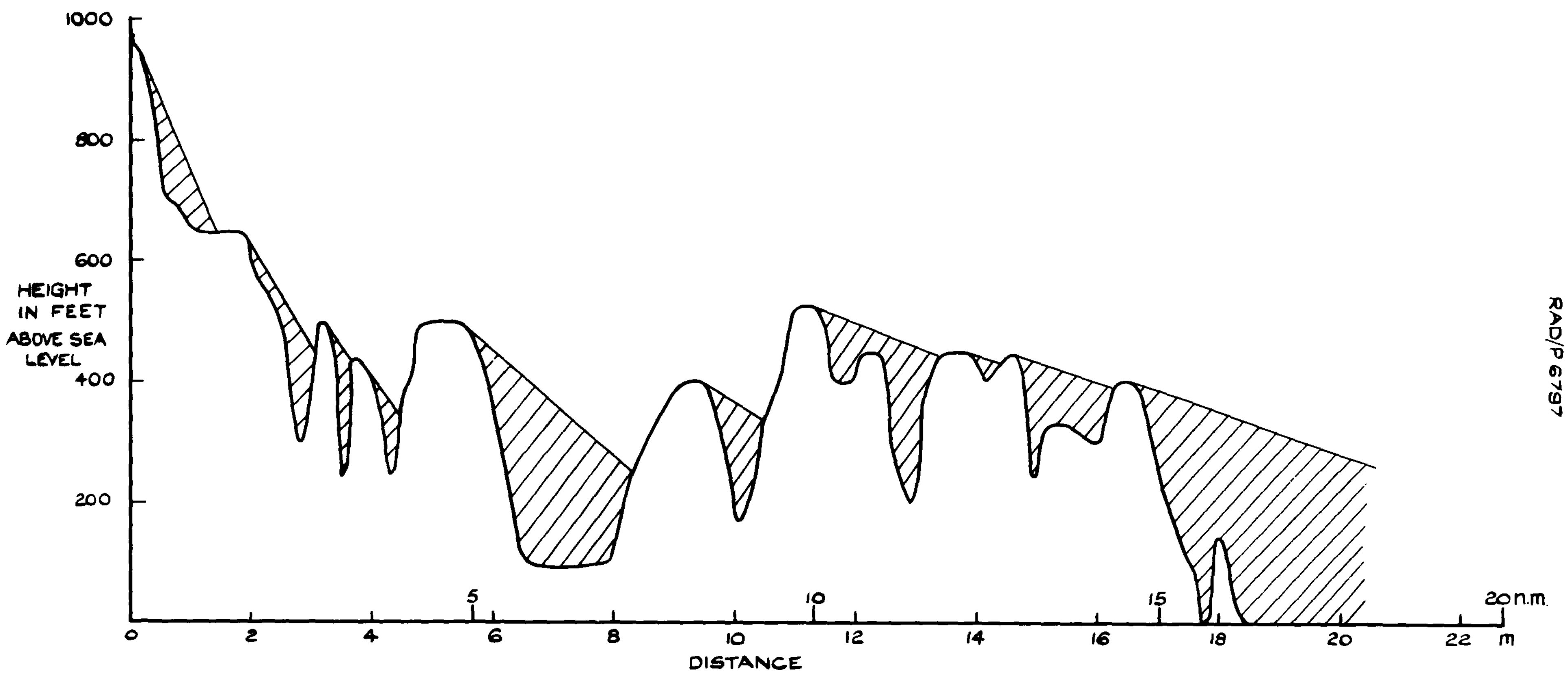


FIG. 21 PROFILE OF TERRAIN ON HEADING 308°T FROM O.P. 21 ABERPORTH

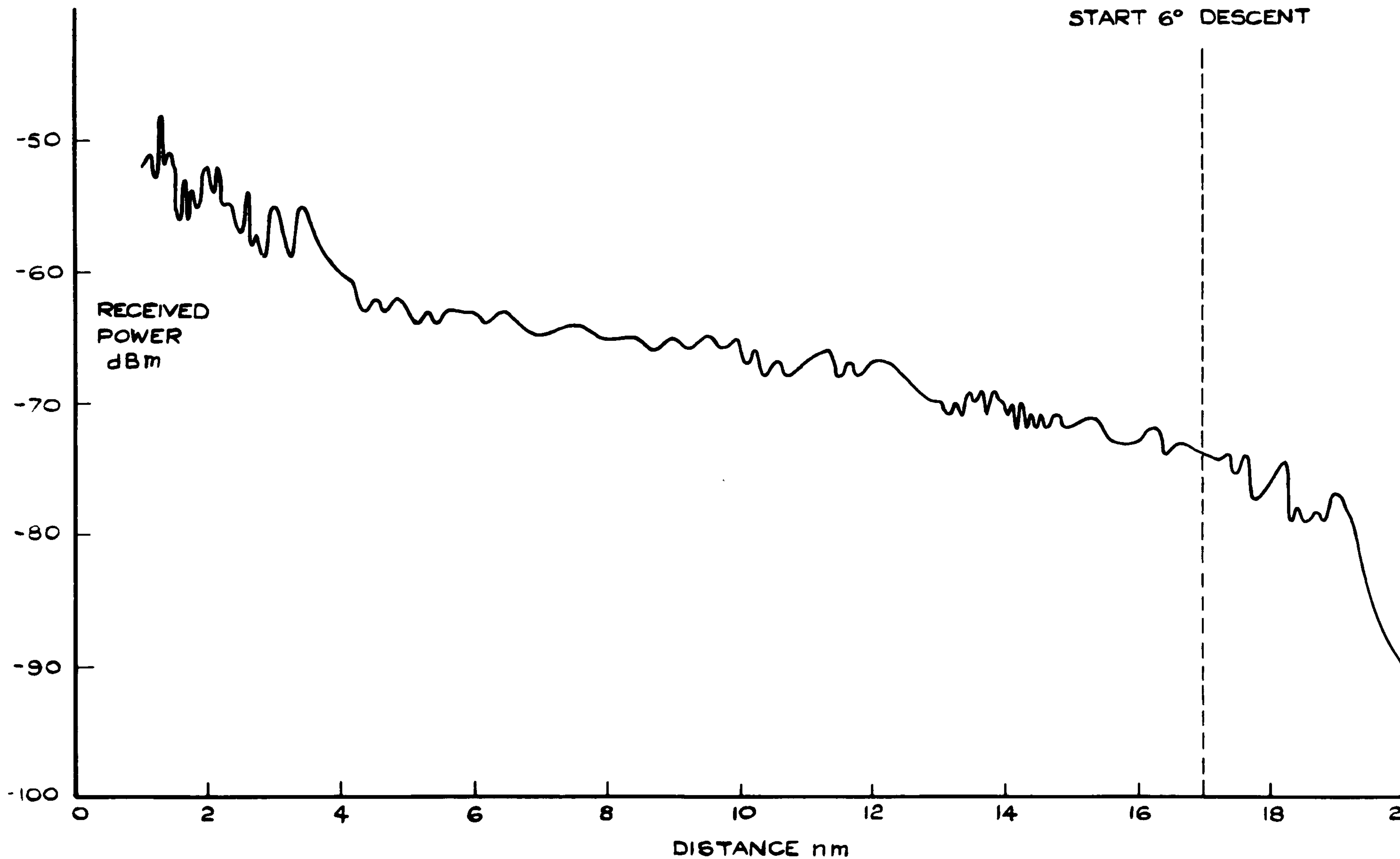


FIG. 22 VARIATION OF RECEIVED POWER VERSUS DISTANCE AT 399·1 Mc/s FOR FLIGHT OVER LAND, HEADING 210° T FROM EWSHOT

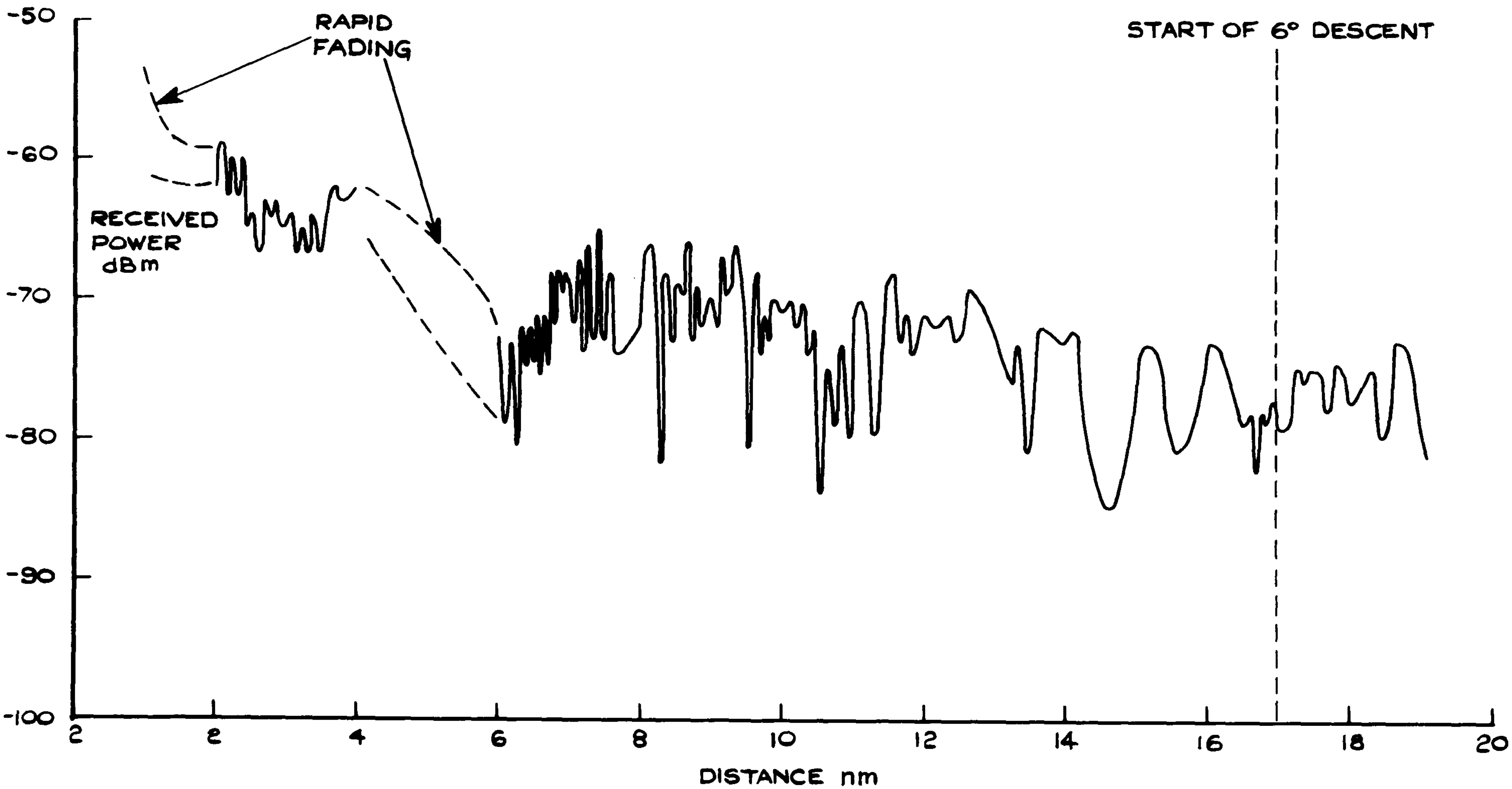


FIG. 23 VARIATION OF RECEIVED POWER VERSUS DISTANCE AT 399·1 Mc/s FOR FLIGHT OVER LAND HEADING 270°T FROM EWSHOT

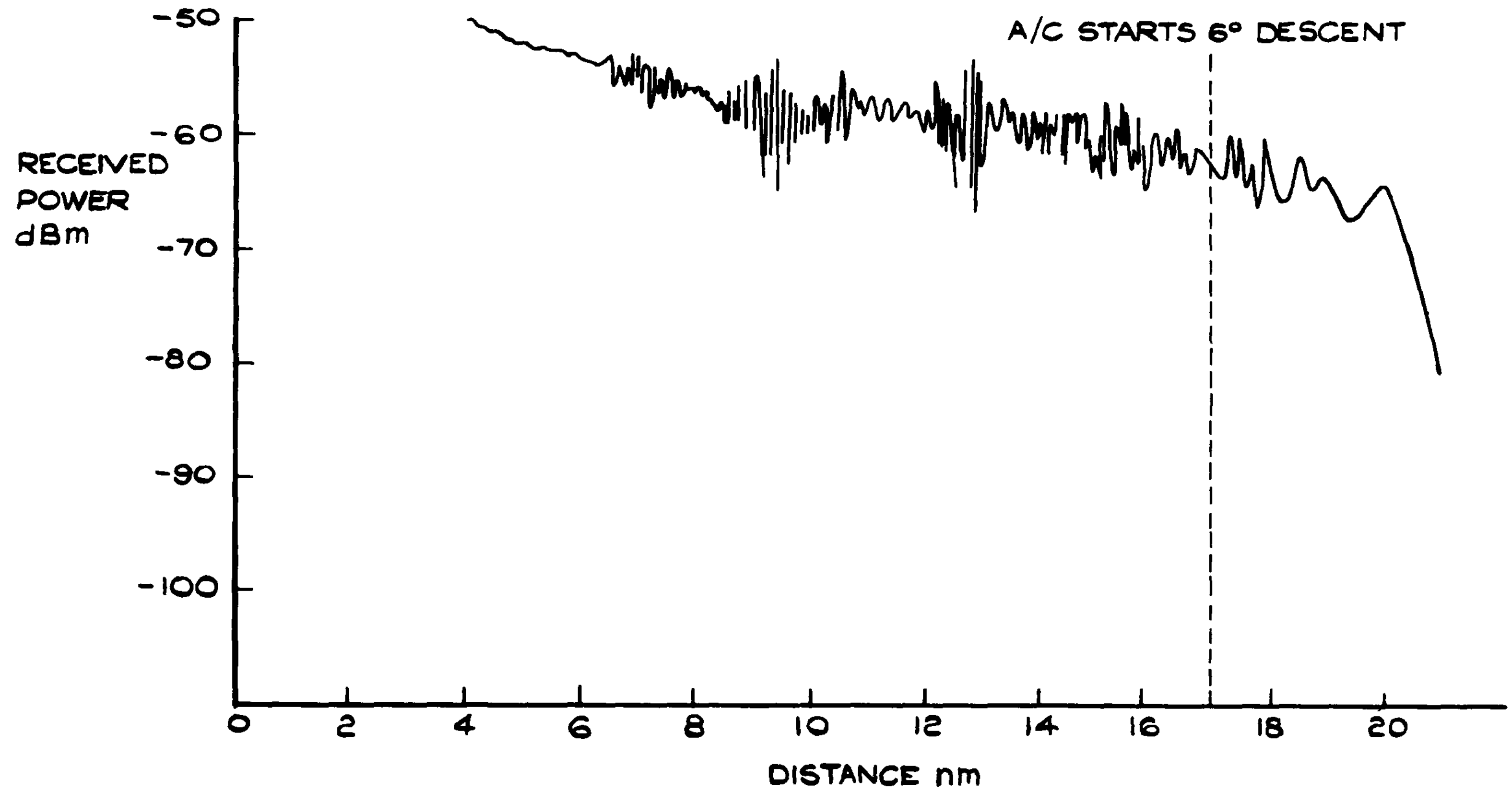


FIG.24 VARIATION OF RECEIVED POWER VERSUS DISTANCE AT 300 Mc/s FOR FLIGHT OVER HILLY TERRAIN HEADING 308°T FROM OP21 ABERPORTH

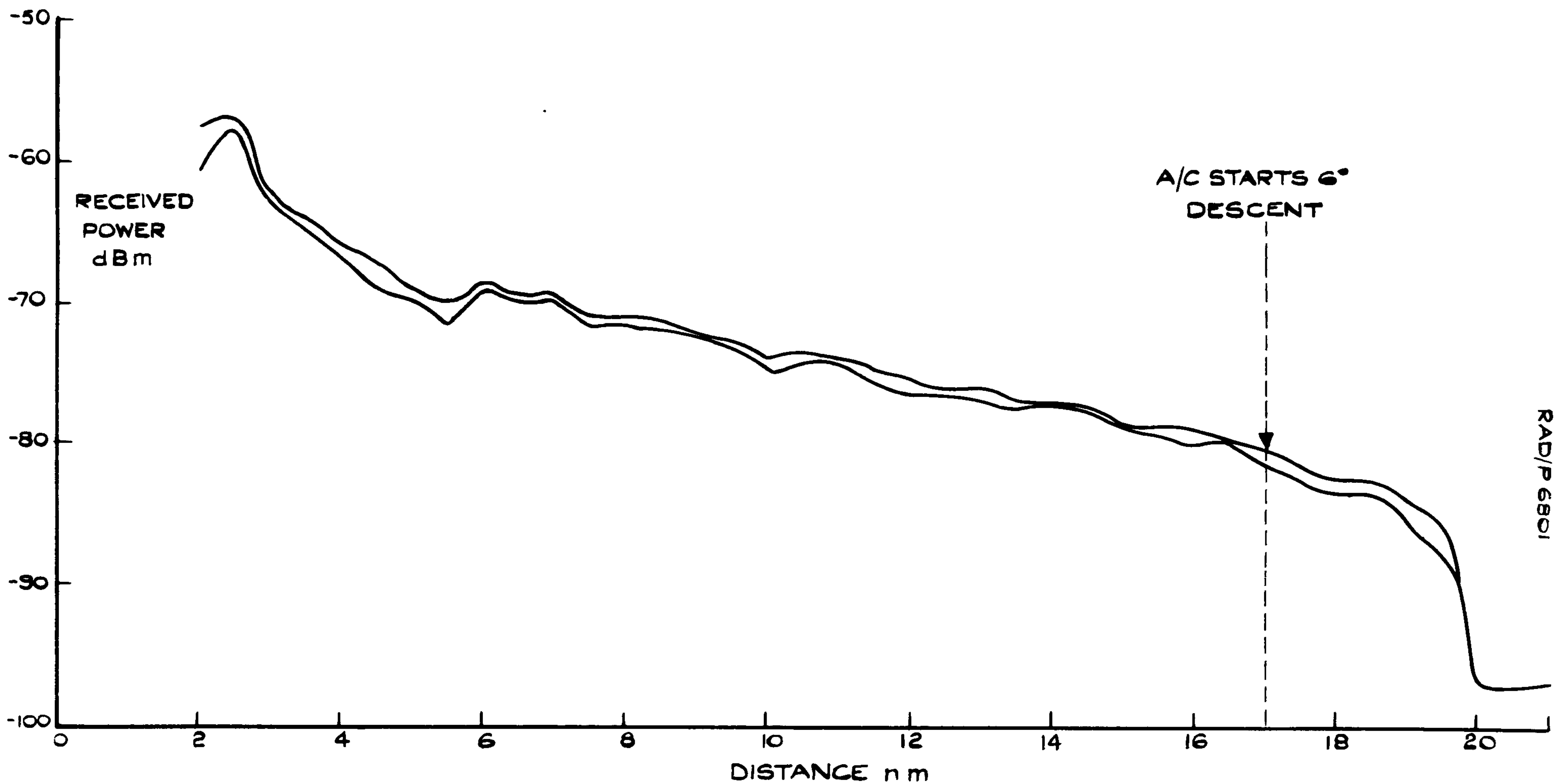


FIG. 25 ENVELOPE OF PEAK TO PEAK FADING AT X-BAND FOR OVER LAND FLIGHT HEADING 210°T FROM EWSHOT

Fig.26

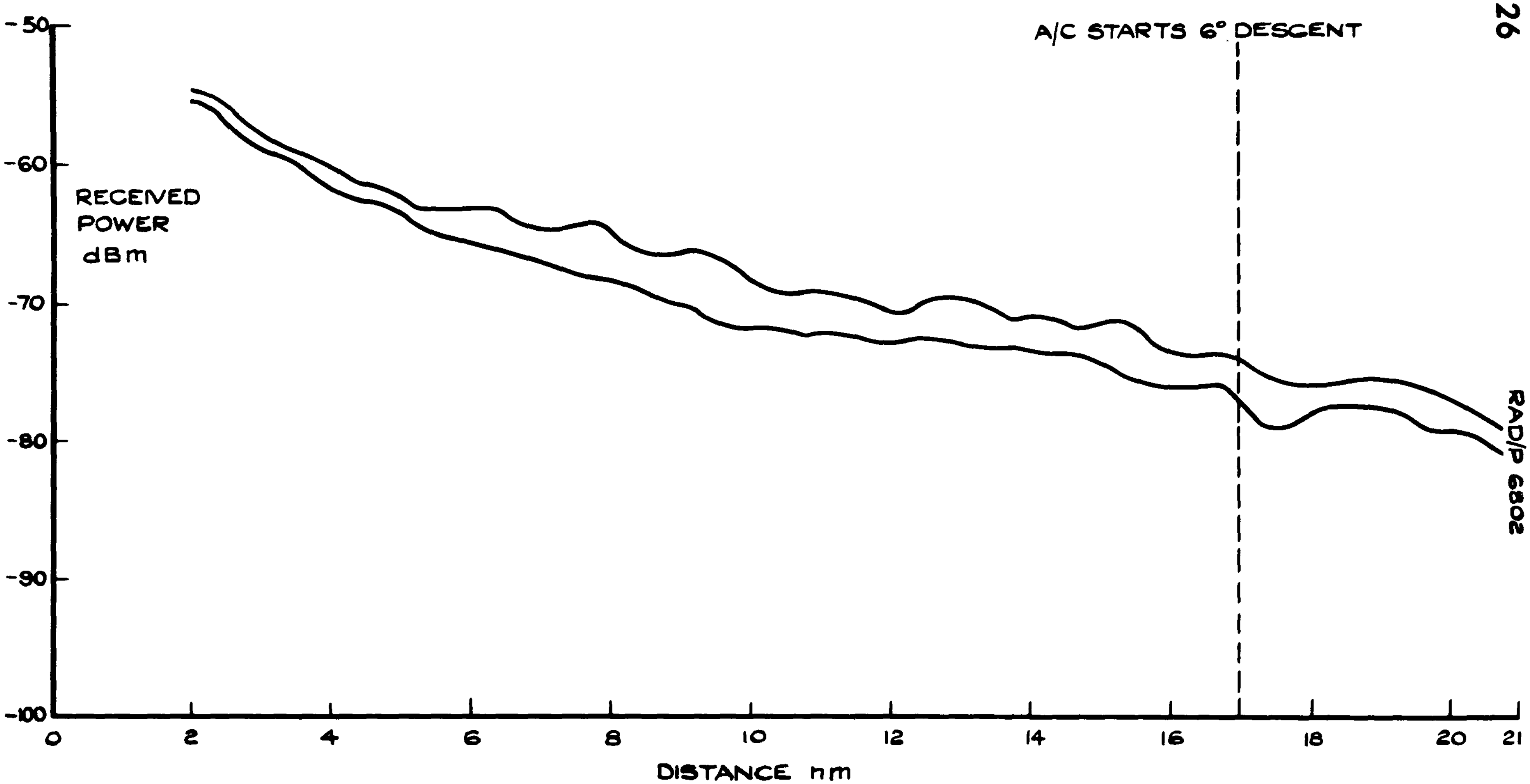


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FIG. 26 ENVELOPE OF PEAK TO PEAK FADING AT X-BAND FOR OVER LAND FLIGHT HEADING 270° T FROM EWSHOT

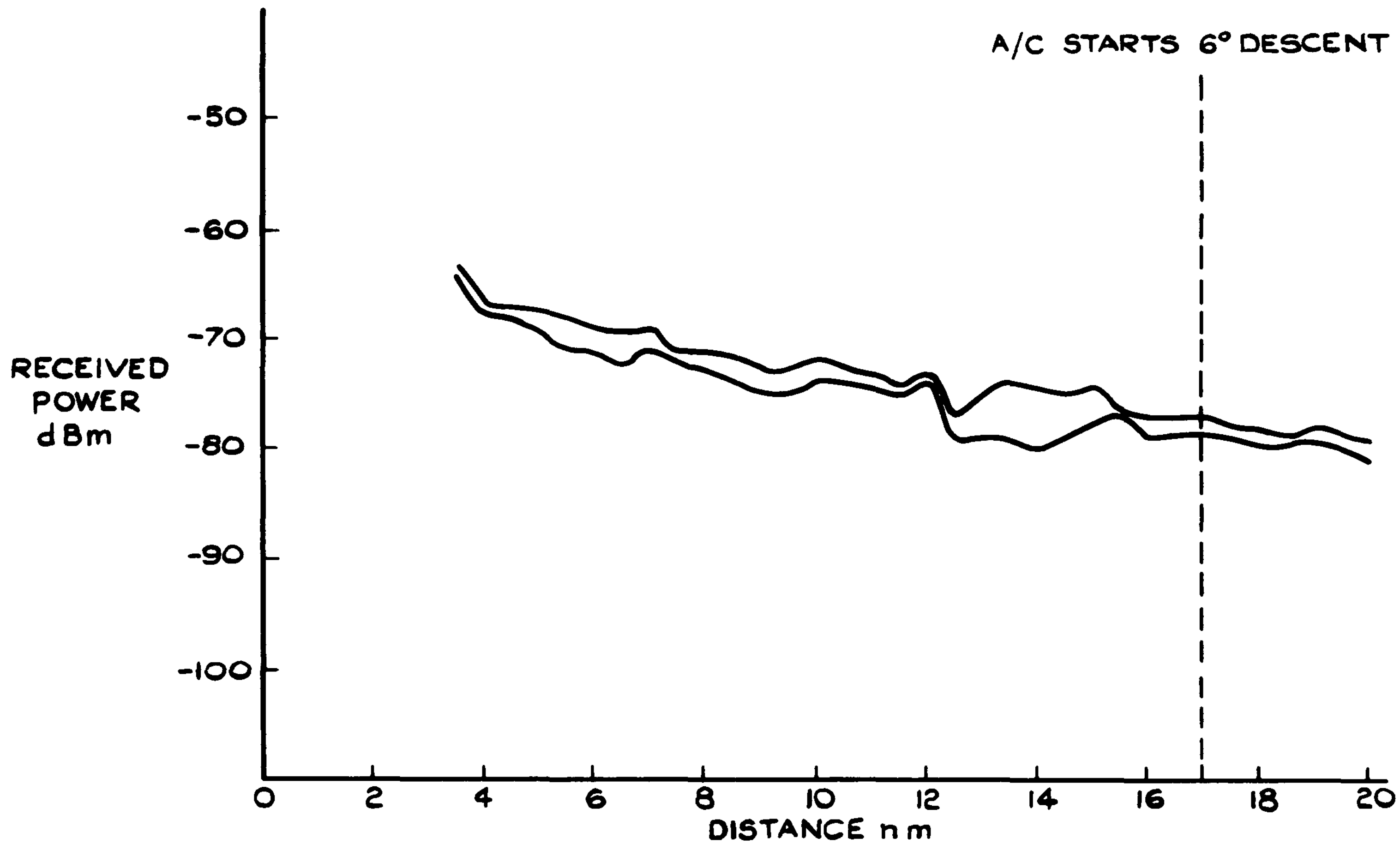

FIG. 27 ENVELOPE OF PEAK TO PEAK FADING AT X-BAND FOR FLIGHT OVER HILLY TERRAIN.
HEADING 30.8°T FROM OP 21 ABERPORTH

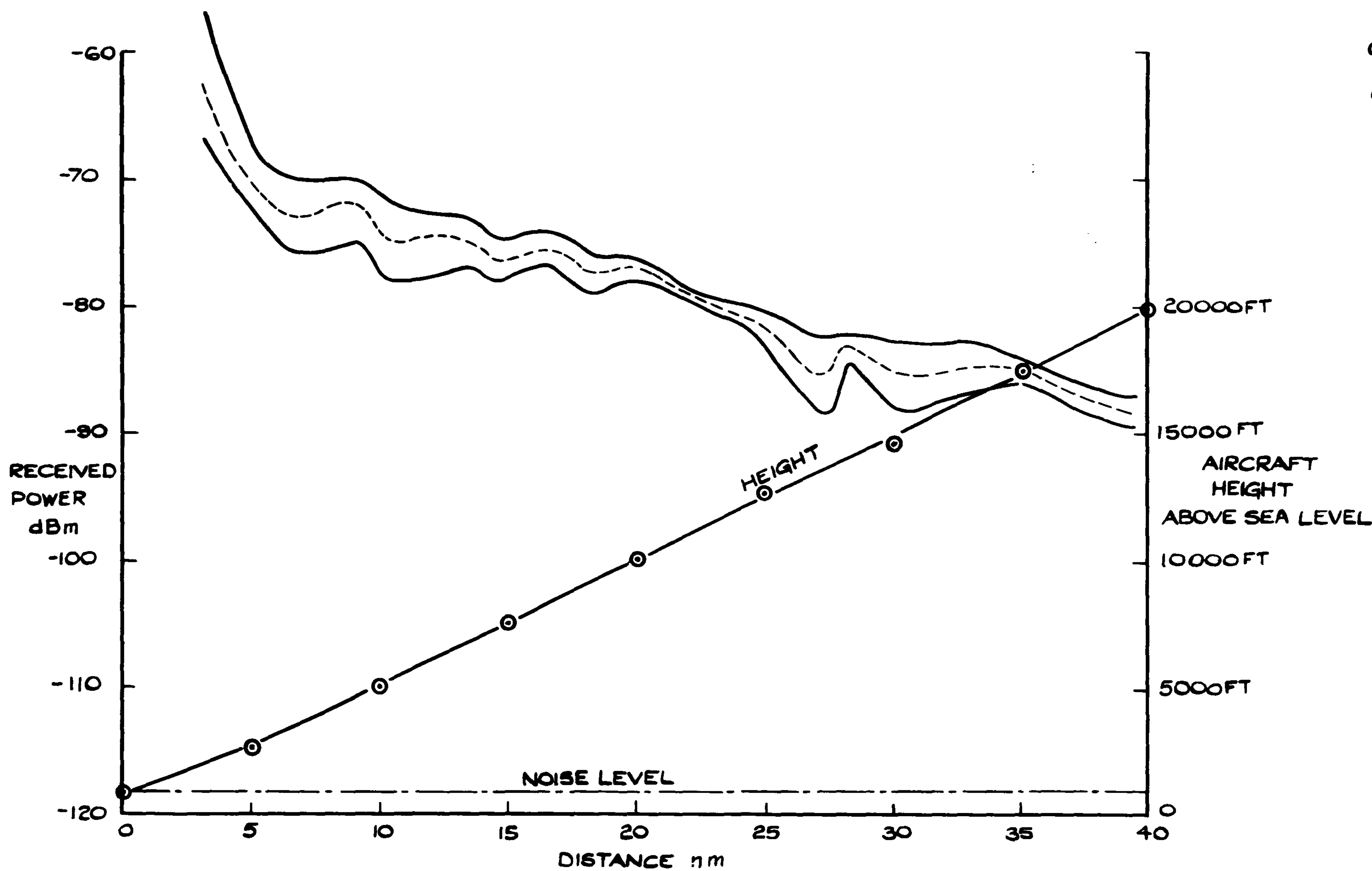

FIG.28 ENVELOPE OF PEAK TO PEAK FADING AT U.H.F. FOR CLIMB TO 20000FT AT 40nm

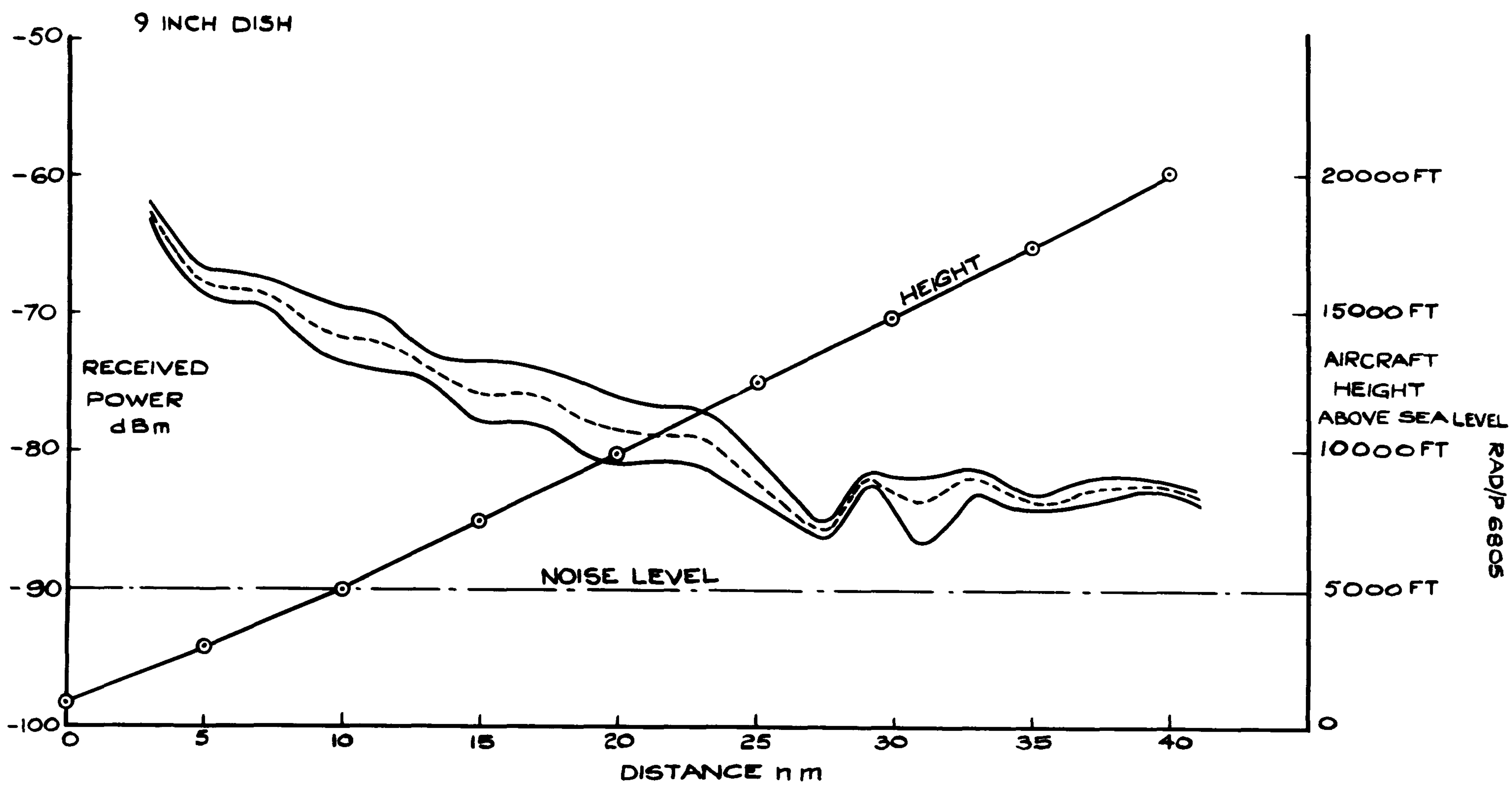

FIG. 29 ENVELOPE OF PEAK TO PEAK FADING AT X-BAND FOR CLIMB TO 20000FT AT 40nm USING 9 INCH RECEIVING DISH

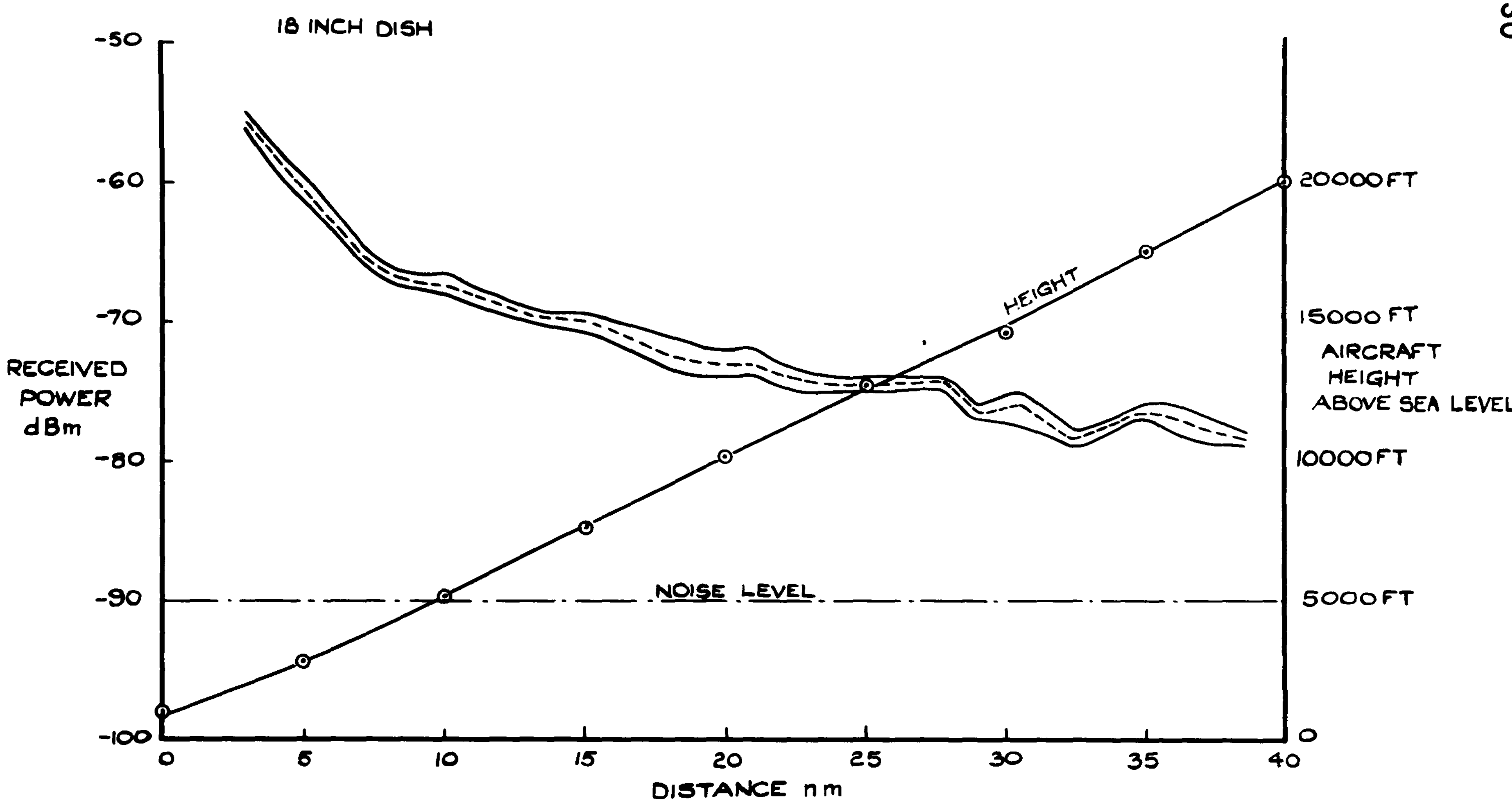

FIG. 30 ENVELOPE OF PEAK TO PEAK FADING AT X-BAND FOR CLIMB TO 20000 FT AT 40 nm USING 18 INCH RECEIVING DISH

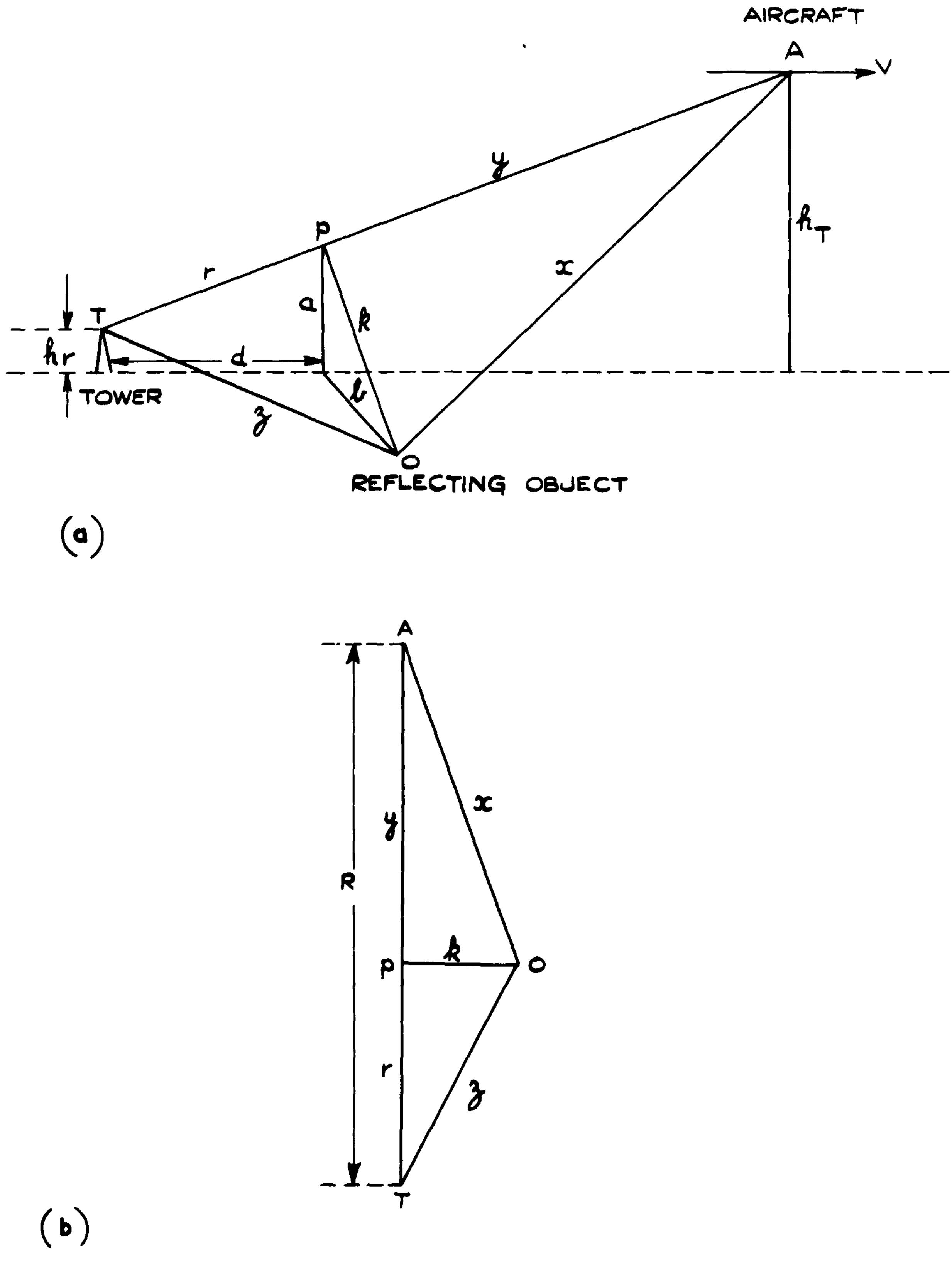
AIRCRAFT
A
V
y
h_T
p
r
x
a
k
T
h_r
d
TOWER
b
z
O
REFLECTING OBJECT
(a)
A
y
x
R
p
k
O
r
z
T
(b)

FIG. A1 (a & b)

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Royal Aircraft Establishment Technical Report 65096 May 1965

Flight trials in support of a Weapons Department research programme were conducted over varying types of terrain and varying sea states, to determine the suitability of U.H.F. or X-band in an air-to-air radio link capable of carrying television and command data.

The results of the over sea trials accorded well with theory except that fading nulls at U.H.F. could be greater than the theoretical value.

Analysis of results of over land flights indicated that at X-band most fades, and at U.H.F. many fades,could be attributed to signal reflection from metallic objects.

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Analysis of results of over land flights indicated that at X-band most fades, and at U.H.F. many fades,could be attributed to signal reflection from metallic objects.

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